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APR 78 R A BRIONES, R F WUERKER F04611-76-C-0053

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FOREWORD

This report was submitted by TRW Defense and Space Systems Group at One Space Park, Redondo Beach, California 90278 under Contract F04611-76-C-0053, Job Order No. 573010BJ with the Air Force Rocket Propulsion Laboratory, Edwards AFB, California 93523.

The authors wish to acknowledge the contribution of Dwight Anthony of TRW, who helped with laser rebuilding. We also want to thank Betty Jackman for preparation of this report and the papers that were generated under the contract.

Finally, we want to thank our technical manager, Dr. Daweel George of AFRPL for help and suggestions throughout the program. Also, we want to thank Mike Adams of AFRPL for his help during the acceptance tests.

This report has been reviewed by the Information Office/XOJ and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public, including foreign nations. This technical report has been reviewed and is approved for publication; it is unclassified and suitable for general public release.

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The feasibility of holographically (three-dimensionally) recording particulate generated by the combustion of small (1/4 x 1/8 x 1/16 inch) solid rocket propellant samples at high pressures (1000 psi) was demonstrated. A new lens-assisted holographic technique gave 3 micron resolution of particles in the combustion environment. Laser pulses of $\leq$ 10 nanoseconds were needed to avoid holographic fringe effects with metallized propellants. Reflected light holograms were also recorded of both particulate and burning propellant. → over

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A double exposure-double reference beam lens-assisted technique was used to record the particle field at two different times. The two recordings could be separately reconstructed. These records gave particle velocities. Equipment (a double reference beam-lens-assisted holocamera and modified pulsed ruby laser illuminator) was built and delivered to the Air Force Rocket Propulsion Laboratory for their own in-house program.

PREFACE

This contract (F04611-76-C-0053) was concerned with the feasibility of holographically recording microscopic particulate and flame phenomena resulting from the combustion of small 1/4 x 1/8 x 1/16 inch solid propellant samples at high pressures. The contract was divided into three phases. The first was concerned with the feasibility and techniques for achieving high resolution. Under Phase I, a new lens-assisted holographic technique was found to give resolutions ($\sim$ 2 microns) higher than had hitherto been achieved.

Phase II was concerned with systematic recording of propellants, the abstraction of quantitative information, feasibility of holographic interferometry, feasibility of reflected light holography, and the development of other more advanced laser and holographic techniques. The holograms were recorded with a Q-switched ruby laser.

One Phase II conclusion was the importance of short (< 10 nanosecond) laser pulses to avoid time-averaged fringe effects obtained with metallized propellants. Another was the development of a double reference beam technique to record holograms on top of one another which could be separately reconstructed. One consequence of this type of recording is the recording of the particle field at two different times. For such a recording, particle motion can be followed and velocities deduced.

Under Phase II, a small 0.5 cubic millimeter portion of one holographic image of combustion was carefully inspected. Each particle in the chosen volume was located (assigned Cartesian coordinates) and measured (568 particles ranging in diameter from 3 - 80 microns were counted). The exercise illustrated the ability to derive quantitative information from a hologram.

The last part of the program (Phase III) was concerned with the fabrication and delivery of equipment which could be used at RPL to record holograms like those recorded under the Phase I and II parts of the program. A new lens-assisted double reference beam holocamera was designed, built, and delivered. Concurrently, an existing RPL laser illuminator (originally built by the authors under contract F04611-69-C-0015) was rebuilt for use with the new holocamera. The laser was upgraded completely and included a multiple pulse capability of 2 - 400 μsec separation between the two laser

pulses. A further feature was the ability to orthogonally polarize the two pulses so that each could be routed along a different reference beam direction. In addition, the rebuilt laser had a pulse chopping capability; the nominal 50 nanosecond pulse was shortened to $\sim$ 10 nanoseconds. The shorter pulses recorded fringe-free holograms of metallized fuels. Details of the new holocamera and laser illuminator are available in the instruction manuals.[1, 2, 3]

1 R. F. Wuerker, "Instruction Manual for a Ruby Laser Holographic Illuminator" (Contract F04611-69-C-0015), February 1970.

2 R. F. Wuerker and R. A. Briones, "Operation Manual for Lens-Assisted Multipulse Holocamera with Reflected Light Option" (Contract F04611-76-C-0053), AFRPL-TM-78-12, July 1978.

3 R. A. Briones and R. F. Wuerker, "Instruction Manual for the Improved Ruby Laser Holographic Illuminator" (Contract F04611-76-C-0053), AFRPL-TM-78-11, July 1978.

CONTENTS

CONTENTS (CONT'D)

NOMENCLATURE

SV	solenoid valve
MV	manual valve
RV	relief valve
GN_2	gaseous nitrogen
M	meter
I_o	initial laser beam intensity
cm	centimeters
λ	wavelength of light
N.A.	numerical aperture
μ	microns (10^{-6} meter)
c	current (amps)
C	electrical capacitance (farads)
A	area
X	separation
V	voltage (volts)
mm	millimeters

FIGURES

I. INTRODUCTION

This study was concerned with the feasibility of holographically (three-dimensionally) recording the combustion of small (typically 1/4 x 1/8 x 1/16 inch) rocket propellant samples at high pressures in a windowed combustion bomb. The original goals, in order of priority, were to obtain:

- particle sizes (to 3 micron diameters),
- particle velocities,
- flame density gradients,
- propellant surface characteristics,

and

- particle size distributions.

Interest in holography centered on its ability to make three-dimensional recordings which one could examine with a microscope. In addition, the intensity and monochromaticity of laser light meant that luminous events, such as solid propellant combustion, could be recorded without fogging of the photosensitive recording plate. Narrow band optical filters and shutters excluded most of the luminous light from the photosensitive holographic plate, yet let the laser light pass through. Types of holography which were to be used included collimated and diffuse transmission holograms, reflected light holography, and double exposure holographic interferometry.

The program was divided into three phases.*

Phase I. Test the feasibility of recording solid propellant combustion in a pressurized window observation chamber. Develop and refine the holographic techniques to give high ($\gtrsim$ 3 micron) resolution.

Phase II. Refine and further develop the holographic techniques developed under Phase I. Systematically record holograms of different Air Force propellants. Analyze and photographically record selected holograms. Investigate multiple exposure holography as a way to deduce particle velocities and flame density effects (via holographic interferometry).

Phase III. Based on the developments from Phases I and II, rebuild an Air Force ruby laser to serve as illuminator and assemble the holographic components into one unit (holocamera). Install and checkout the modified and new equipment at the AFRPL.

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* The statement of work is reproduced in Appendix I.

II. PHASE I - SETUP AND PRELIMINARY COMBUSTION HOLOGRAMS

The most immediate goal of Phase I was to record holograms of solid propellant at high pressures. This meant setting up the Air Force combustion bomb in a safe area, building a rudimentary holographic optical arrangement around the combustion bomb, contending with the problems of film fogging (due to the lumination from the propellant combustion), and recording a few holograms to show feasibility and uncover problems.

The combustion bomb and first holographic arrangement were set up on a 4 x 4 x 3/4 foot solid granite table (in Building R1, Room 1059, TRW). The laser was set up in an adjoining room. The beam passed through a hole in the door between the two rooms.

The bomb was pressurized through electrically actuated valves. The valves were interlocked to the doors into the room in such a way that the bomb could never be pressurized until the doors were closed.* The pressurization system schematic is presented in Figure 1. The bomb was pressurized from either 6,000 lb/in^2 or 2,500 lb/in^2 commercial bottles of dry nitrogen in the same room as the laser. Reference to the figure shows that there were three electrically actuated valves; SV-1 (normally closed), SV-2 (normally closed), SV-3 (normally open). In addition, there were manual valves (MV-1, MV-2, MV-3, MV-4, and MV-5), a rupture disk (RD-1, 2000 lbs/in^2), and relief valves RV-1 and RV-2 (each 1200 lbs/in^2). The safety circuit is shown in Figure 2 and, although simple, was reliable. Note that the system cannot be pressured until the doors are closed.** The two door switches activated the nominally closed high pressure valve (SV-1) and the normally open dump or vent valve (SV-3). Closing the switch, between the power supply and the door interlock, opens the high pressure valve and closes the dump valve, thereby pressurizing the system. Closing the second switch opens the flow valve (SV-2), fires the ignitor, and fires the laser.

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* The bomb stored 3,000 joules of compressed gas when pressurized to 1000 psi. This amount of energy is enough to be dangerous. On the other hand, it compares with the energy in the ruby laser's capacitor bank.

** The approved operating procedure is reproduced in Appendix II.

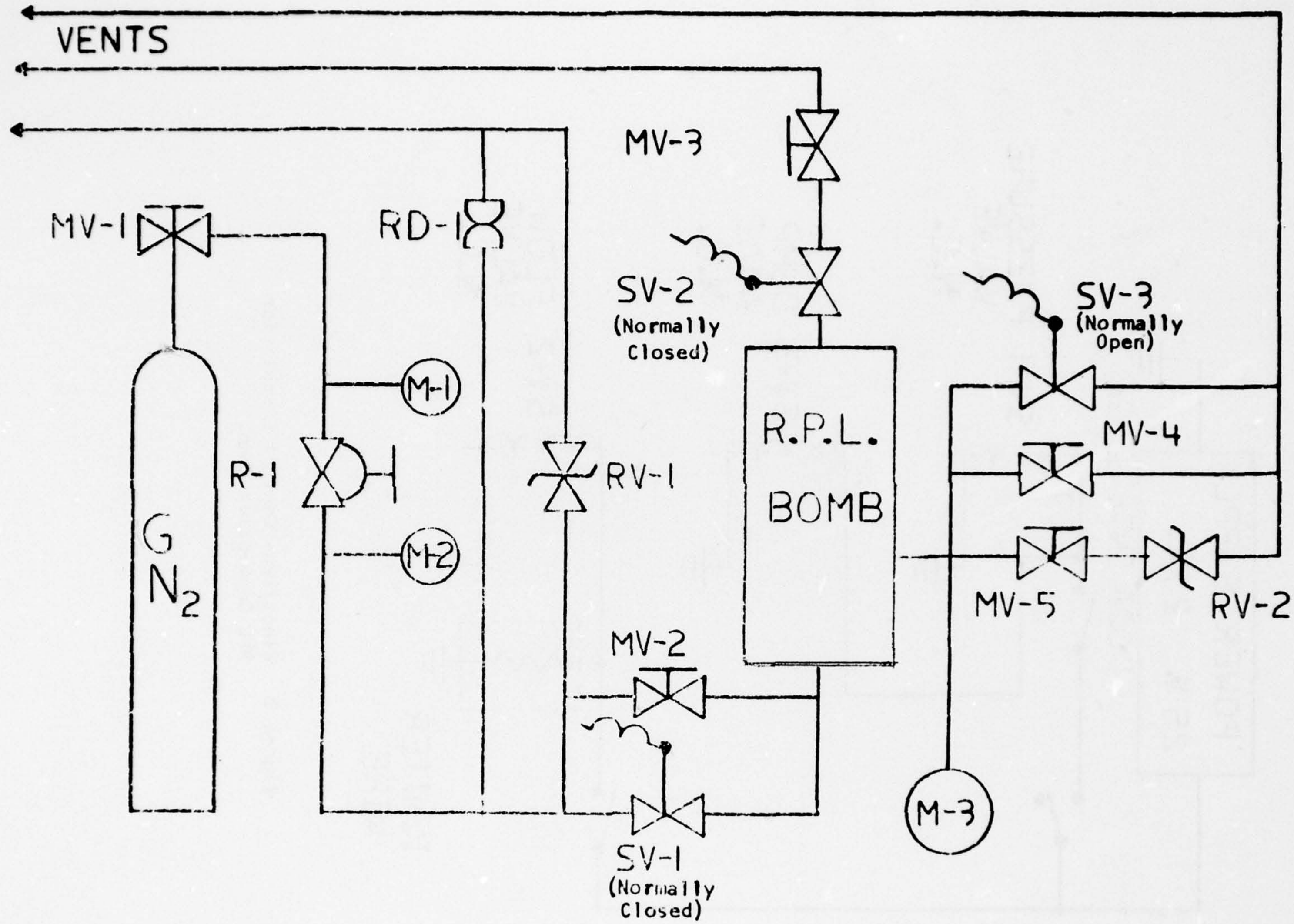

Figure 1. Pressurization System Schematic for R.P.L. Combustion Bomb.

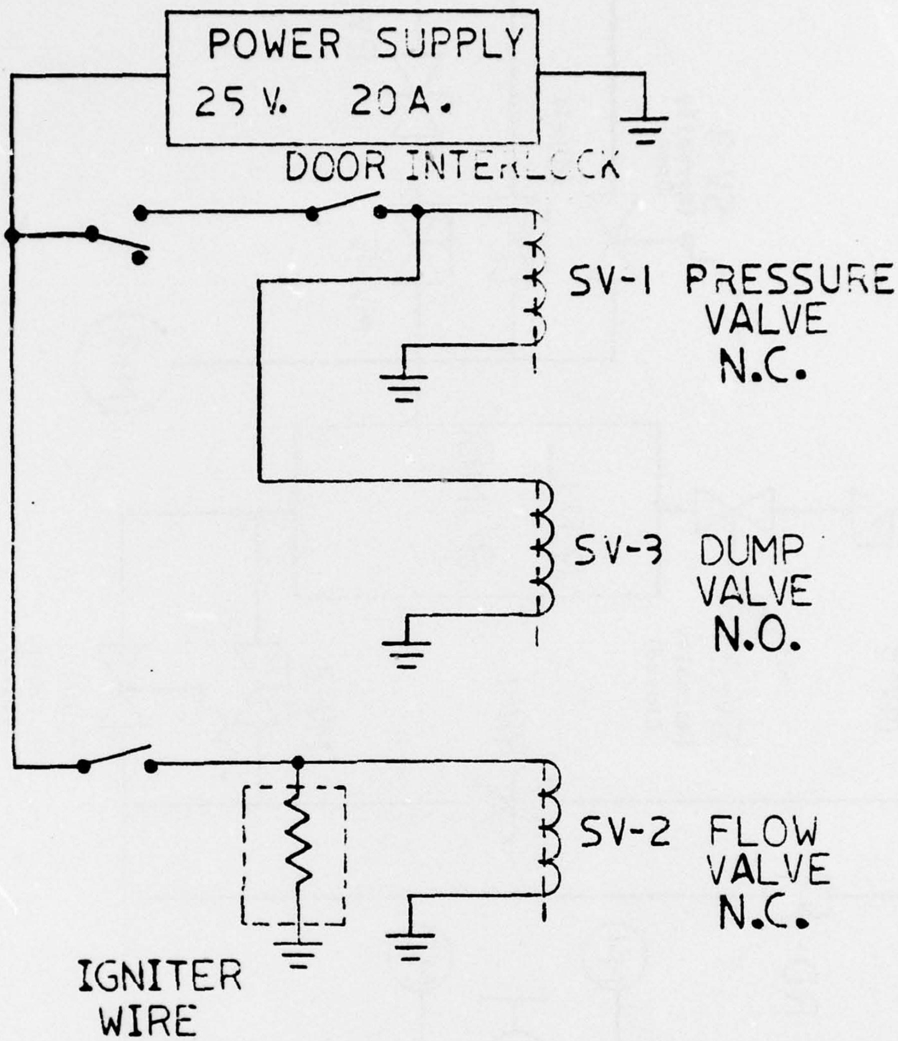

Figure 2. Electrical Control Circuit for RPL Combustion Bomb.

Figure 3 is a view of the laboratory setup looking from the control room at the combustion bomb and holographic optics, all set up on the 4 x 8 x 3/4 foot granite block table. During a combustion run, the double doors were closed and the ruby beam fired through a 2-inch hole in one door. Power supplies for activating the valves and igniting the propellant are seen below the ruby laser (nominally 1/2 joule, 50 nanosecond, Q-switched). Figure 4 is a closer view of the granite table, holographic setup, combustion bomb, the high pressure plumbing, and (in the foreground) a helium-neon laser. The latter was used to record static holograms, with the holographic optical arrangement, for the purpose of testing improvements or effects (on resolution) due to changes of wavelength between the recording and reconstructing steps. The electrically activated control valves were mounted to the far side of the plywood board at the end of the granite table. Figure 5 is an even closer view of the combustion bomb at the time when the focused image holography was being tested.

An isometric view of the combustion bomb is presented in Figure 6, showing two of the three viewing windows, the method of assembly, and the internal propellant sample, mounted to a pedestal on the end plug.* Figure 7 is a photograph of the end plug with 1/4 x 1/8 x 1/16 inch fuel sample mounted and ignitor wire in place. The miter box used to cut fuel samples is also seen in this picture. The method of suspending the combustion bomb above the table can also be seen in this picture.

A cross sectional view of the combustion bomb is seen in Figure 8. This figure shows that the combustion bomb has three window ports, two of which were opposed. For the setup seen in Figures 3, 4, 5, and 7, the illuminating laser beam passed through the small (1/2 inch diameter x 0.8" thick) fused quartz window through the combustion zone and exitted (toward the hologram) through the larger (1 1/2" dia. x 0.8 inch) opposing window. The other 1 1/2 inch x 0.8 inch window was used later to record reflected light holograms. A dimensioned engineering drawing of the combustion bomb is presented in Figure 9.

* Not shown is the fact that during combustion gas flowed through a line connected to the end plug (via Valve SV-1 in Figure 1). The high pressure line had to be opened to remove the end plug, or whenever propellant samples had to be replaced. The line was electrically interlocked to the pressurization system to insure that the bomb could not be pressurized unless the line was connected.

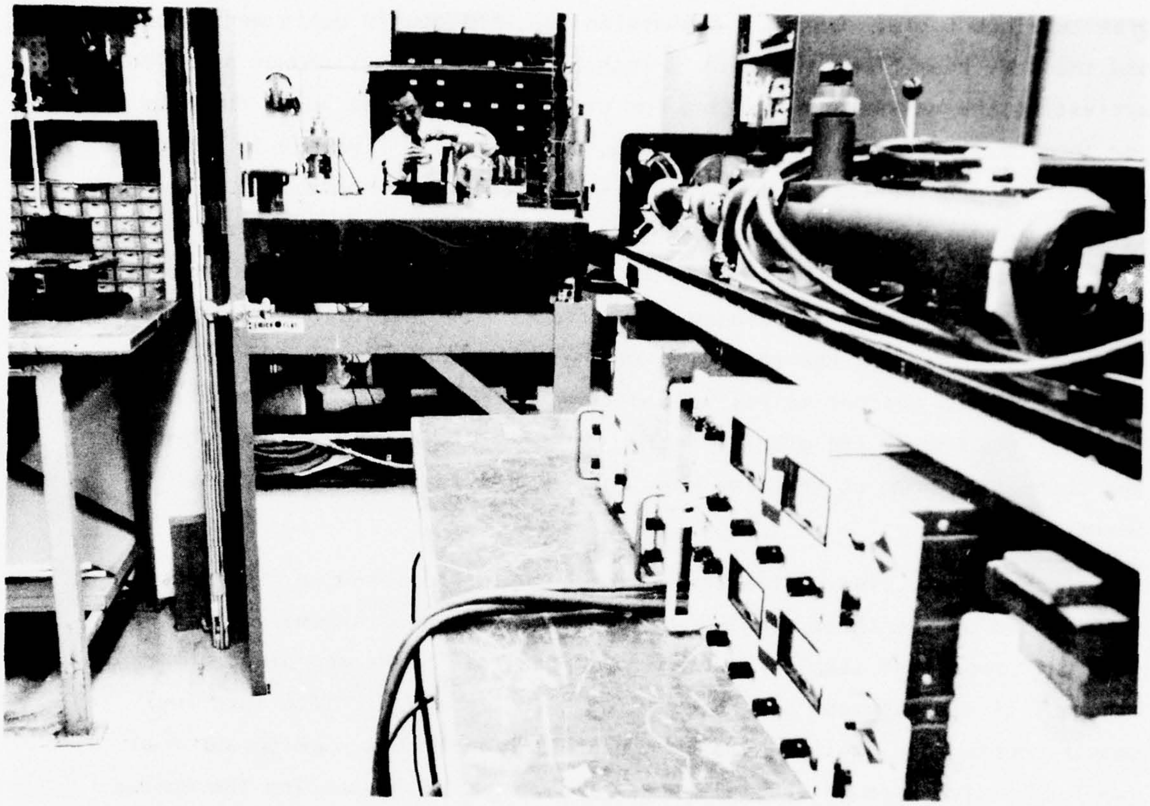

Figure 3. Photograph of the ruby laser (right foreground), combustion bomb, holographic optics, and setup on granite table in an adjoining room. R. A. Briones is in this picture.

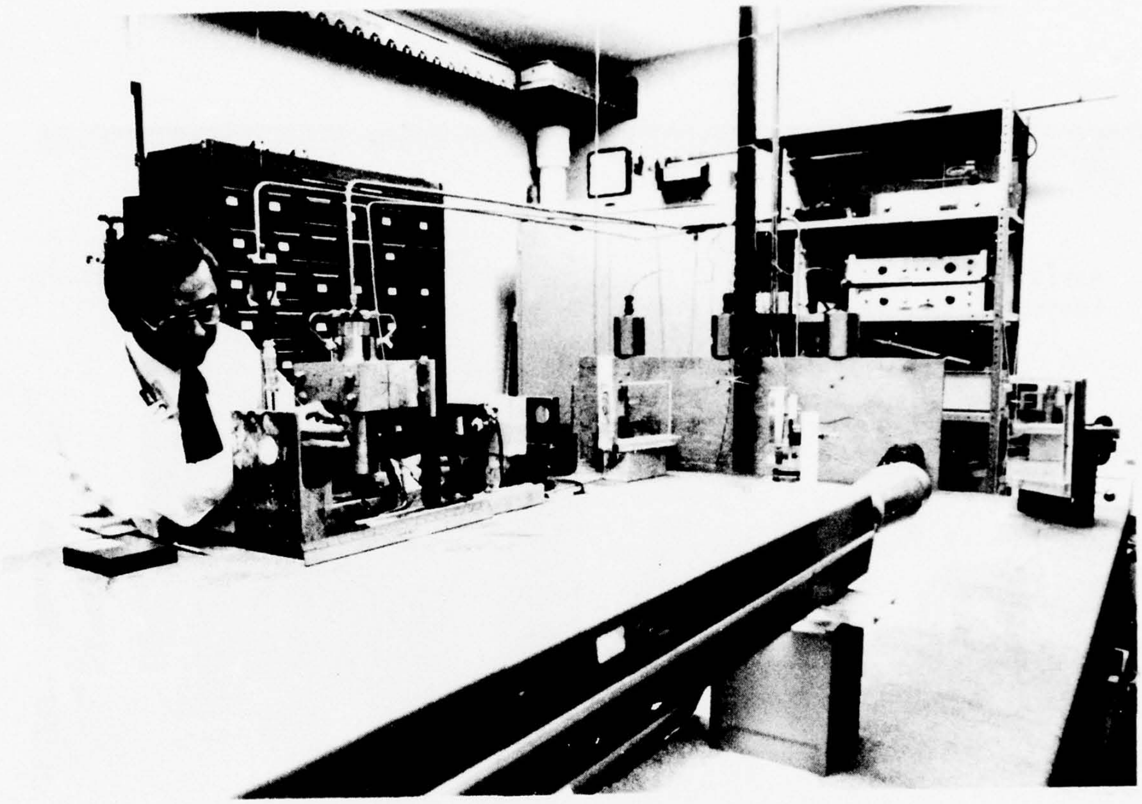

Figure 4. Closer view of the experimental holographic setup.

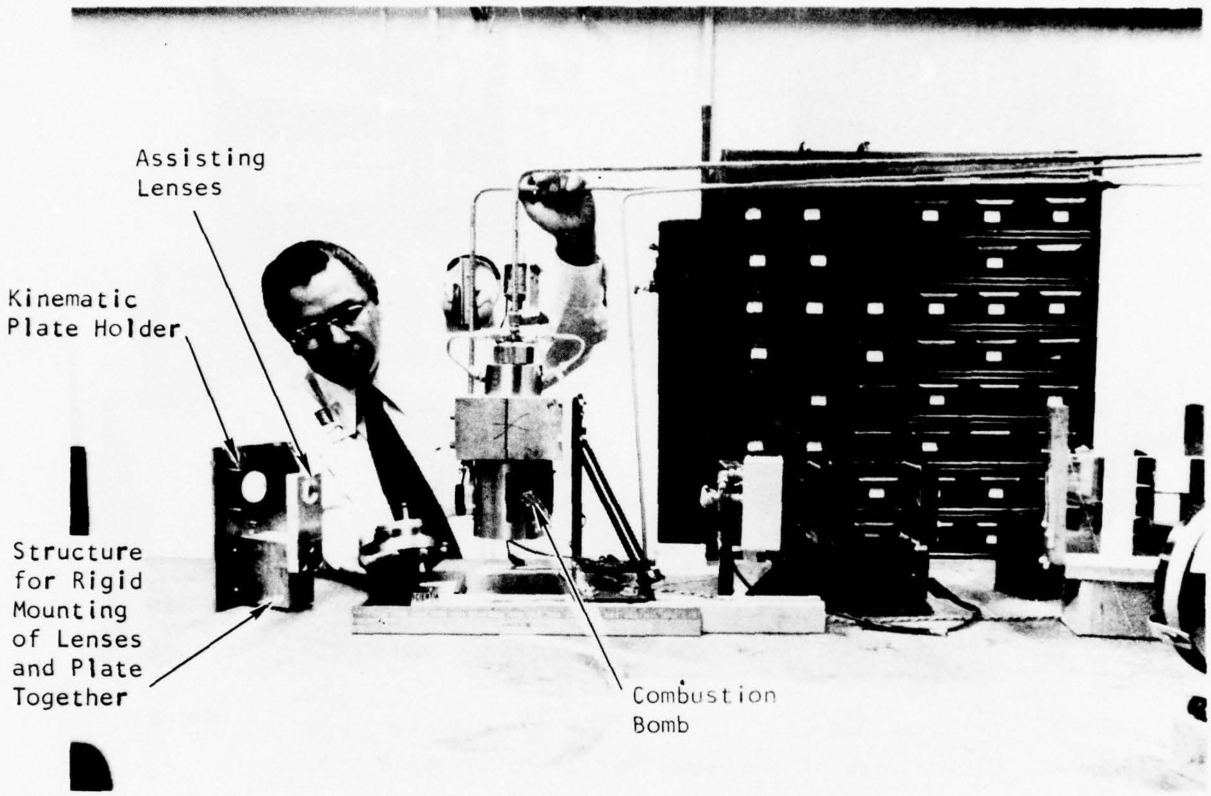

Figure 5. Even closer view showing the combustion bomb and the lenses and plate holder used in the focused image test. The lenses and plate holder have been set aside.

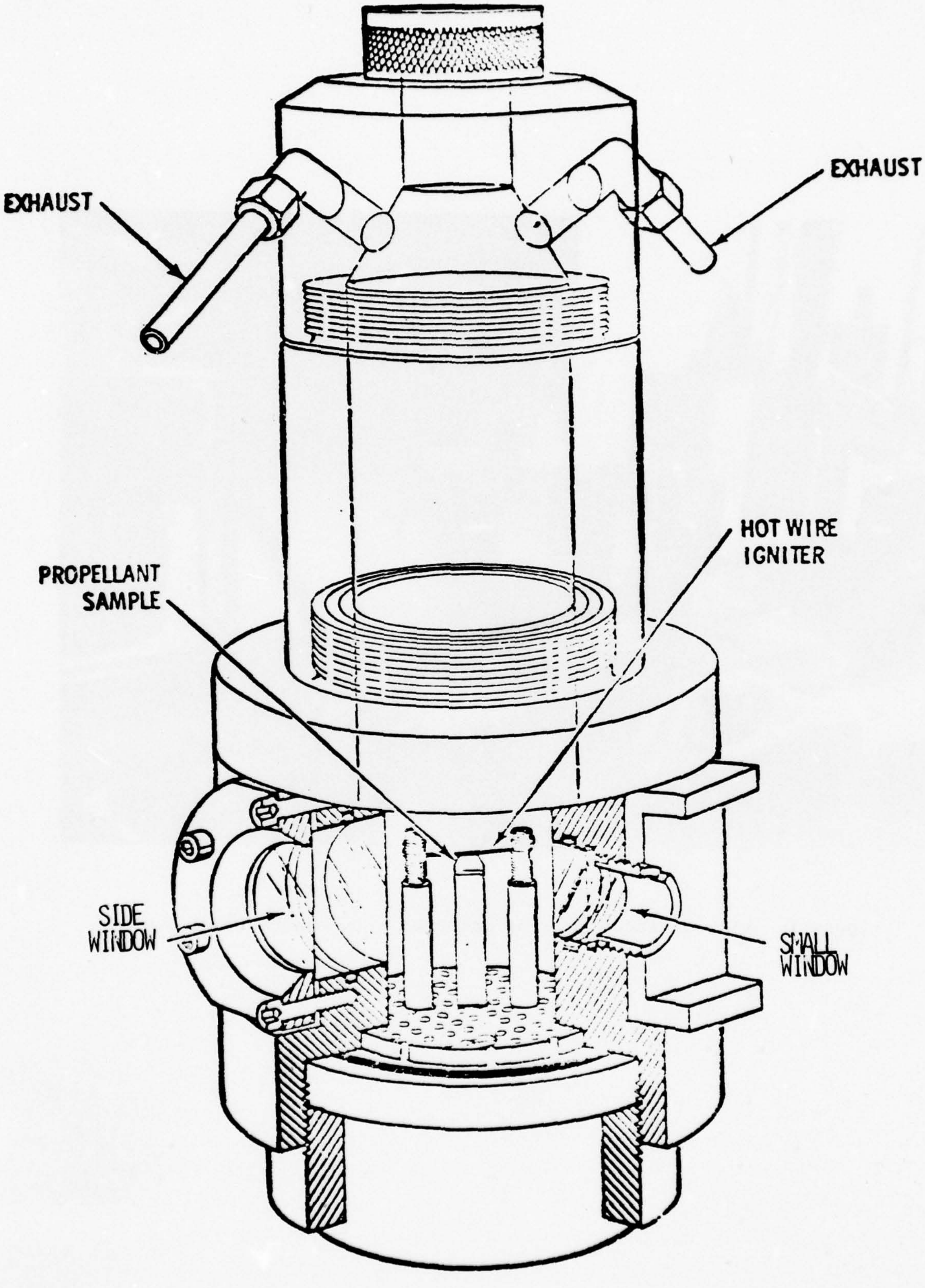

Figure 6. Isometric View of RPL Combustion Bomb.

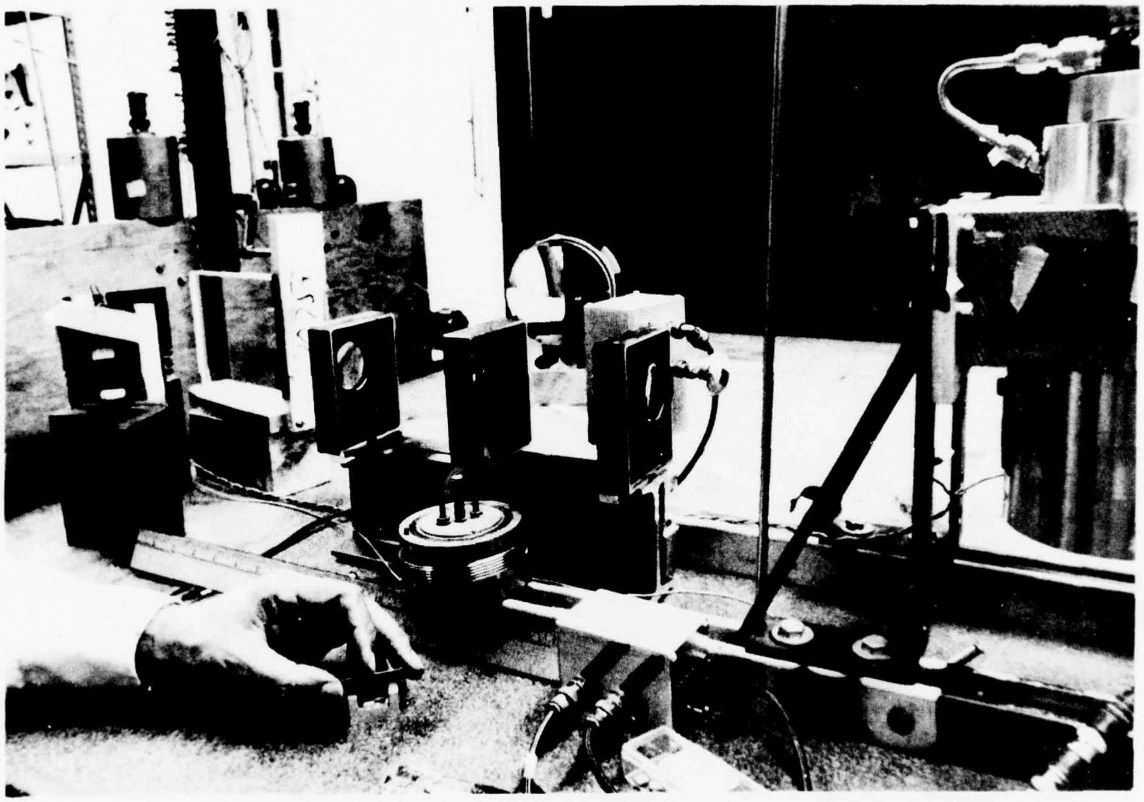

Figure 7. View of setup showing end plug with mounted fuel sample.

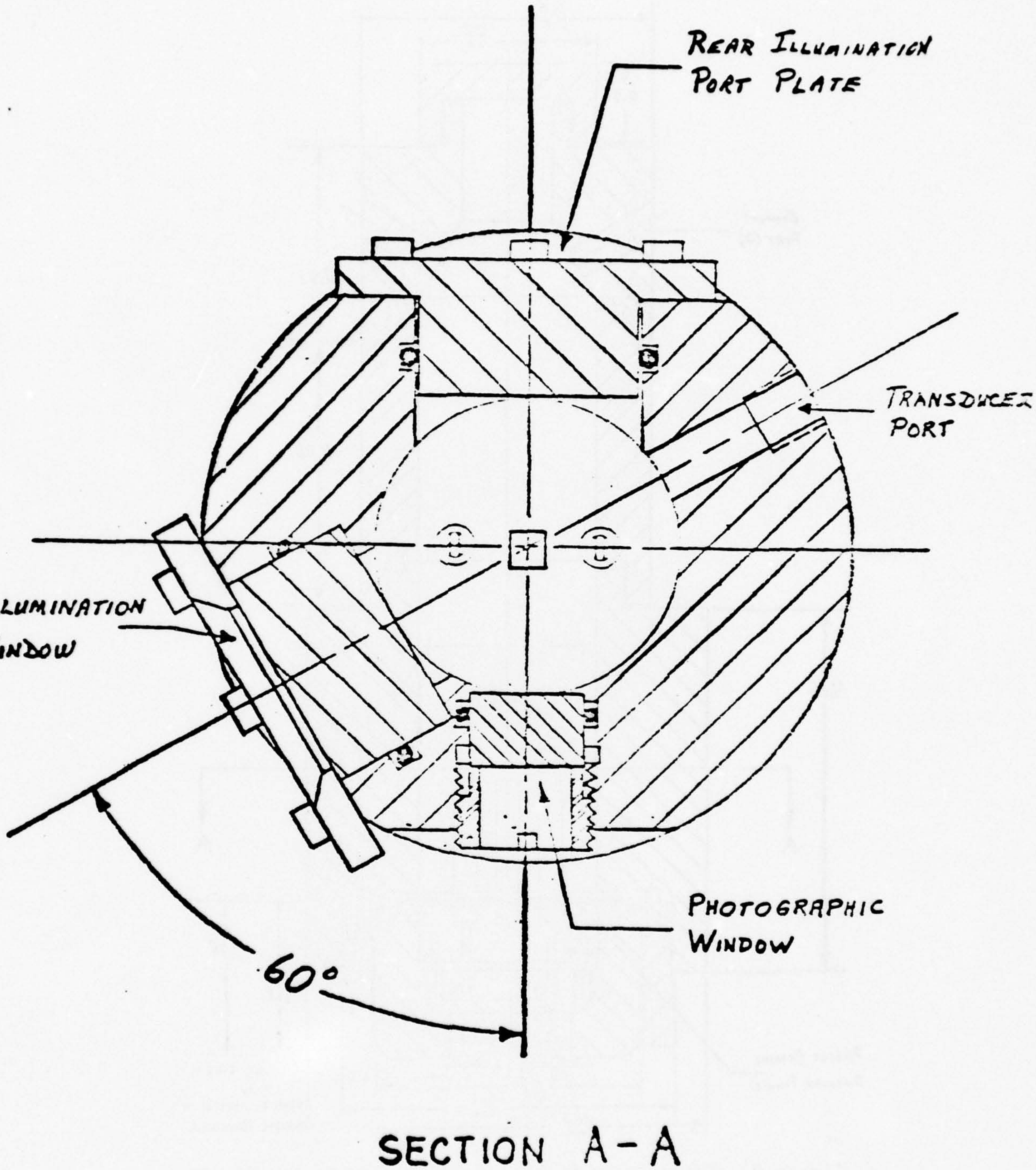

Figure 8. Top View of RPL Combustion Bomb.

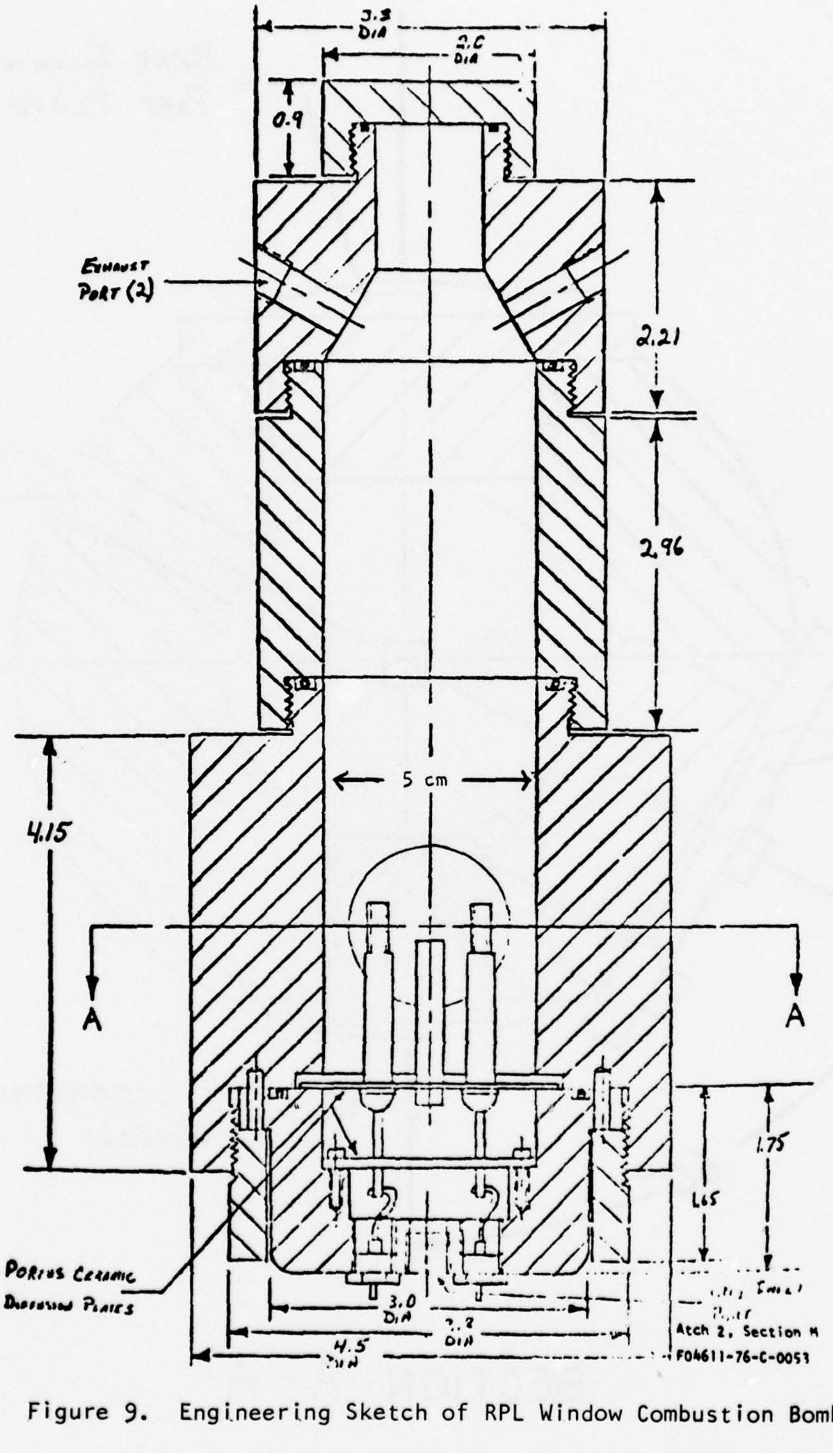

Figure 9. Engineering Sketch of RPL Window Combustion Bomb.

Figure 10 is a picture looking from the combustion bomb back toward the illuminating ruby laser in the adjoining room. At the time this picture was taken, a fuel sample was fired with the intent of illustrating the luminosity of the combustion of the small propellant samples at high pressures. Metallized fuels were particularly luminous, enough to require a narrow band optical filter to keep the plates from being fogged. Fuels which were used on this program are summarized in Table I.

Table I

THE SOLID PROPELLANTS

Type	% Solids	Oxidizer	Fuel/Other	Burn Rate at 1000 psia (in/sec)
NT-10	87	AP	0.5% ZrC 0.5% C	.5
MS-23	87.5	AP	1.0% Zr 0.5% C	.54
MX-70	87	AP	15.75% Aℓ 3.0% Ferrocene 0.75% FeF_3	1.69
ANB-3066	88	AP	18% Aℓ	.36
NB-79	88	AP	20% Aℓ	.43
NB-122	90	AP	21% Aℓ	.15
NB-123	90	AP 15% HMX	21% Aℓ	.49

At the start of the program, an extremely simple transmission holographic optical arrangement was set up around the combustion bomb for the purpose of establishing initial feasibility. The arrangement is shown in Figure 11. In this figure, the beam from the ruby laser illuminator passes first through a glass wedge which divided it into the holographic scene and reference beam components. The reference beam is the light reflected from the front surface of the wedge. The scene component is the preponderant amount of light (90%) which passes through the wedge and was incident on a 90° glass prism. The prism reflects the laser light into the combustion bomb through the small window. The coherent

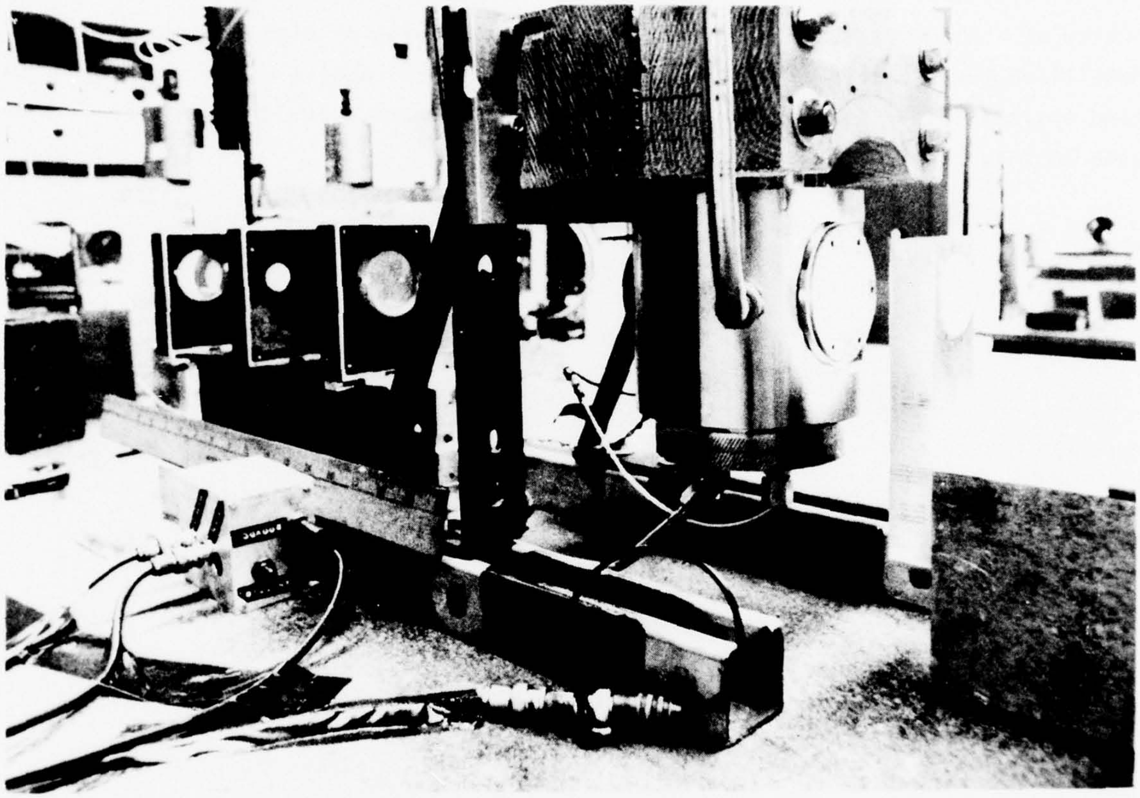

Figure 10. View of combustion bomb when propellant was being fired.

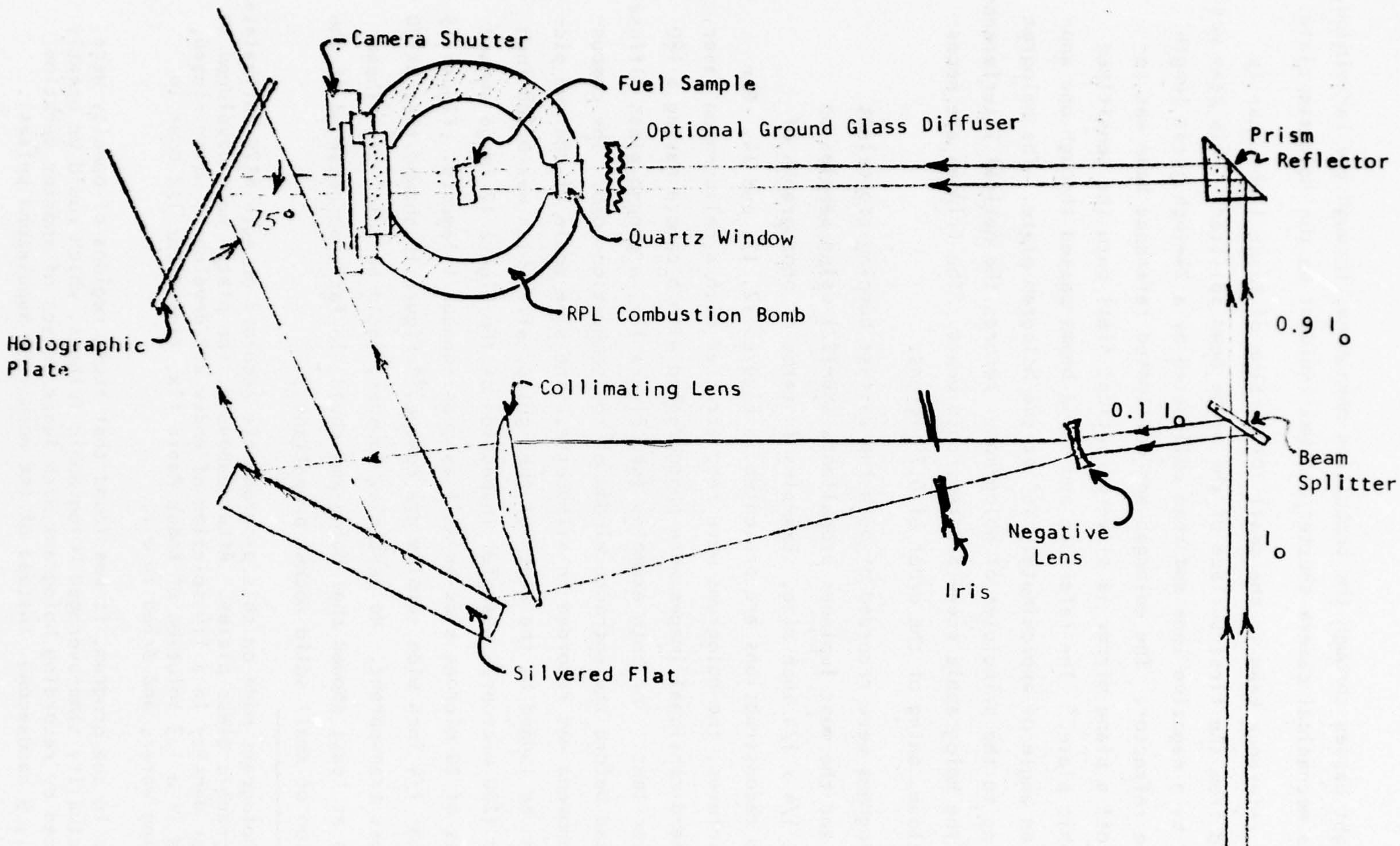

Figure 11. Schematic of Holographic Arrangement Constructed Around RPL Combustion Bomb.

laser light passes through the combustion phenomena, through the far window, through a mechanical camera shutter, and was incident on the hologram plate.

The reference beam is the small 10% portion of laser light that is reflected from the first surface of the wedge beam splitter. This beam was expanded by a negative lens and then collimated by a 24-inch focal length telescope refractor. The enlarged and collimated reference beam was reflected off a plane mirror (a silvered optical flat) onto the sensitized holographic plate.* The reference and scene beams passed through one another at an angle of approximately 75° at the hologram plate. The hologram (according to the principles of holography) records the optical interference between the holographic scene and reference beams. The fringes are necessarily close, being of the order of 0.7 microns.

Holograms were recorded of both the fastest burning propellant (MX-70) and the most luminous propellants (MB-122) using samples up to 1/4 x 1/4 x 1/4 inch size. Examples in terms of photographs of hologram reconstructions are presented in Figures 12, 13, and 14. For these pictures, the holograms were reconstructed with a helium-neon laser. The three-dimensional images were photographed with a camera having a 180 millimeter lens. For both examples (see Figure 11), a ground glass diffuser was placed before the entrance window of the combustion bomb. The combustion phenomena was recorded in silhouette. The size scale of the two pictures can be judged by the width of the ignitor wire, which was 0.008 inch diameter (200 microns). Careful inspection of the Figure 12 image showed particles of 20 microns size as well as quasi-opaque filaments. Figure 13 shows that 1/4 inch wide samples are opaque.** Figure 14 showed that MX-70 was almost transparent. No particles, however, could be resolved. These examples at least showed that holograms could, in fact, be recorded of the combustion of small solid rocket propellants.

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* All holograms made on this program were recorded on Agfa 8E75 antihalated holographic glass plates. After exposure, the plates were developed to proper density in a 1:4 solution of Kodak HRP developer, water rinsed, fixed in a 1:3 solution of Kodak Rapid fix, rinsed for 1/2 hour in running water, and dried in air.

** Later in the program, it was found that these regions of opacity were in actuality time-averaged holographic fringes, which could be greatly reduced by recording holograms with laser pulses of shorter duration (i.e., 5 nanosecond instead of the normal 50 nanosecond pulses).

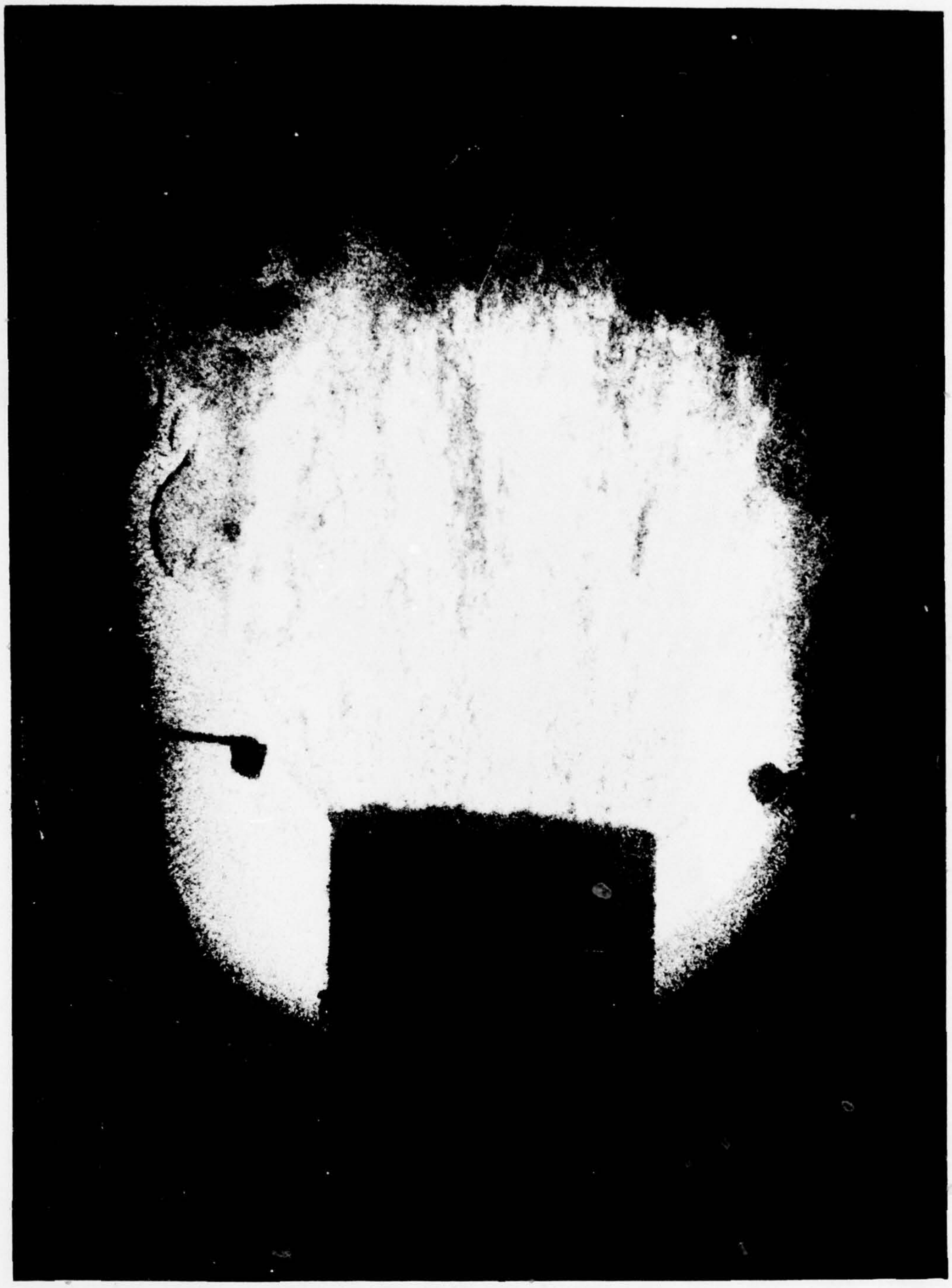

Figure 12. Photograph of the reconstruction of a hologram of the combustion at 500 lbs/in^2 N_2 of 1/4 x 1/4 x 1/16 inch sample of NB-79 propellant burning in the RPL combustion bomb. The hologram was recorded in the Figure 11 two-beam holographic apparatus with rear ground glass illumination. The reconstruction was photographed at f/11.

Figure 13. Photograph of the reconstruction of a hologram of the combustion at 500 lbs/in^2 N_2 of 1/4 x 1/4 x 1/4 inch sample of NB-123 burning in the RPL combustion bomb (reconstruction photographed at f/8).

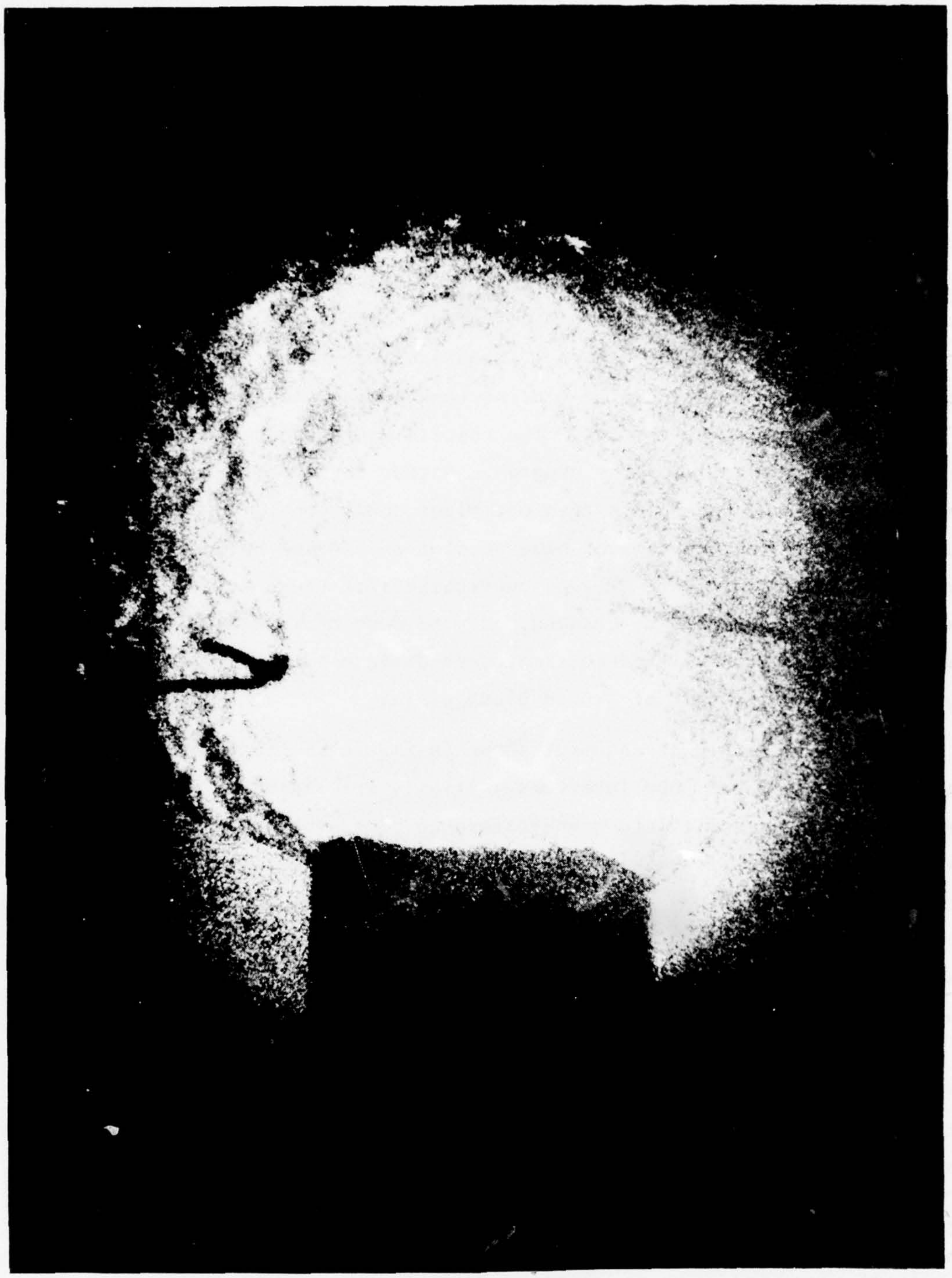

Figure 14. Photograph of the reconstruction of a hologram of the combustion at 500 lbs/in^2 N_2 of 1/4 x 1/4 x 1/16 inch sample of MX-70 fuel burning in the RPL combustion bomb (reconstruction photographed at f/11).

III. PHASE I - RESOLUTION MEASUREMENTS

The Figure 11 holographic arrangement did not give particularly good resolution. Particles smaller than 20 microns could not be seen. The setup was tested statically using a 1951 resolution chart as the test object.* The widths of the bars for different columns and row numbers are amassed in Table II. The Figure 11 apparatus was found to give reconstructions with a resolution of 8 microns when ground glass was inserted. and 3 microns when it was removed. The results were encouraging, but not high enough for the goals of the program. Rather than record more holograms of combustion, under less than optimized conditions, it was decided to concentrate on the problems of high resolution. A new holographic arrangement, shown in Figure 15, was constructed for these tests. The reference beam angle could be changed, and the mode of illumination could be changed quickly, from either collimated or diffuse type of illumination by the insertion of a pair of ground glass plates.

For the holographic arrangement shown in Figure 15, the beam from the illuminating Q-switched ruby laser was initially collimated to 12 cm diameter. It was next split into scene-reference components by a large wedge beam splitter. The reference beam was reflected off a metallized optical flat which travelled along an ellipse. As a result, the reference beam angle could be varied, yet maintain path match with the scene beam. The scene beam was reflected off a pair of front surface mirrors onto the hologram. The mirror spatially matched the scene and reference beams when the ground glass diffuser was withdrawn. The resolution chart was six inches away from the hologram, which closely approximated the closest distance of combustion phenomena in the bomb. Holograms were recorded at scene-reference beam angles of 30, 45, 60, 75, and 90 degrees.

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* The 1951 resolution chart is a series of vertical and horizontal three-bar patterns whose spacing decreases according to the following equation.

$$\text{Spacing} = 2^{\left\{\text{Column Number} + \frac{\text{Row \#} - 1}{6}\right\}} \text{ Line Pairs/Millimeter} .$$

The resolution of any optical apparatus is determined by seeing how far down the pattern can be read. A practical definition is half the readable bar spacing.

Table II

BAR WIDTHS OF USAF 1951 RESOLUTION TARGET IN MICRONS

	COLUMN NUMBER							
ROW NO.	0	1	2	3	4	5	6	7
1	500 μ	250 μ	125 μ	62.5 μ	31.3 μ	15.6 μ	7.81 μ	3.91 μ
2	446	223	111	55.7	27.9	13.9	6.96	3.47
3	397	198	99.2	49.5	24.8	12.4	6.20	3.11
4	355	177	88.3	44.2	22.1	11.0	5.52	2.76
5	315	158	78.7	39.4	19.7	9.84	4.90	2.46
6	281	140	70.1	35.0	17.5	8.77	4.39	2.19

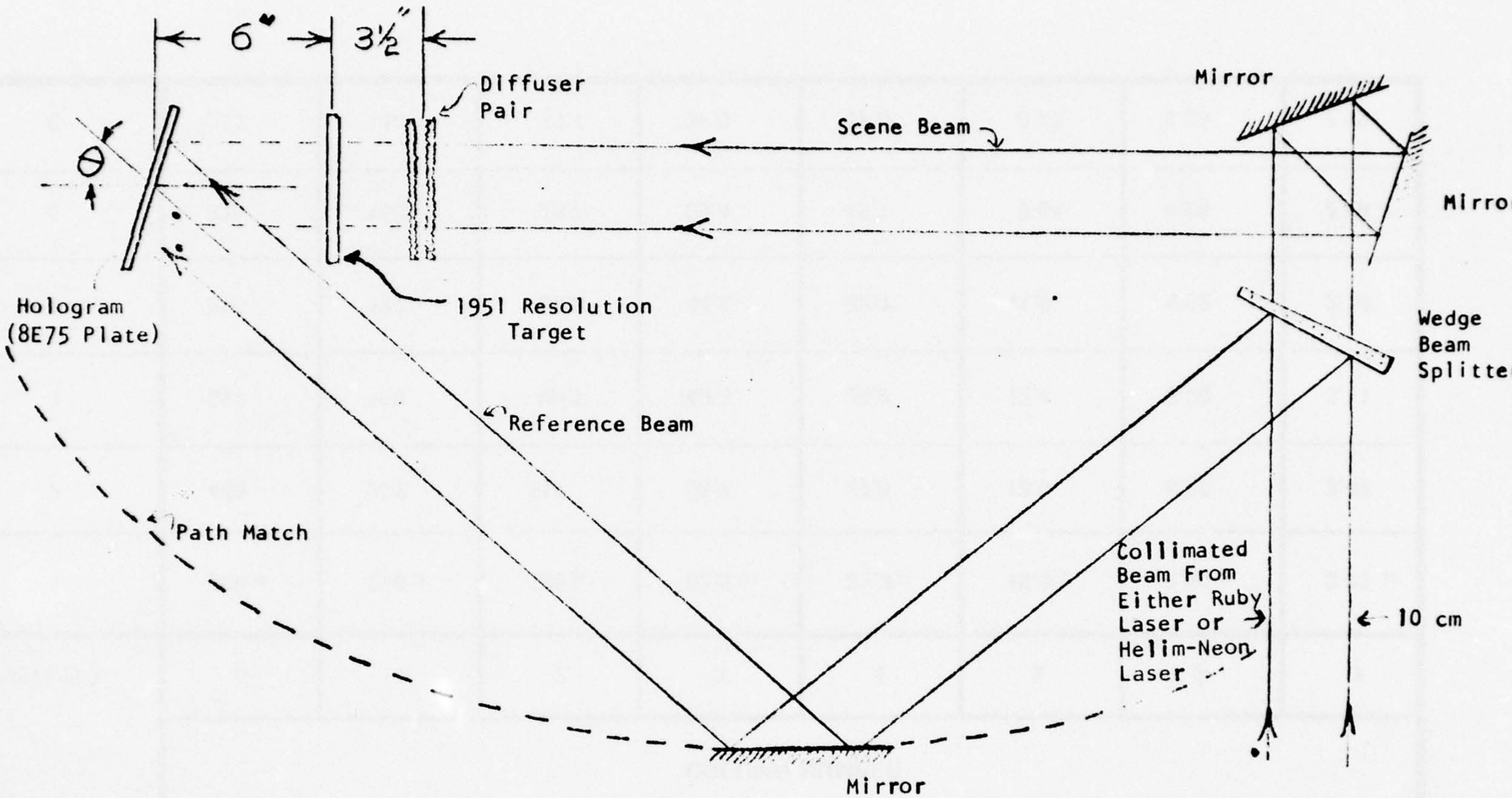

Figure 15. Schematic of Holographic Arrangement Used to Test Resolution as Function of Scene-Reference Beam Angle and of Different Illumination Schemes.

The mode of illumination consisted of either direct or collimated illumination at two different scene-reference beam ratios, or diffuse illumination with the pair of ground glass diffusers either just behind the resolution target, 3-1/2 inches behind the resolution target, focused to infinity by a 20" focal length collimating lens, or imaged on the hologram by a pair of the same lenses. The latter type approximates the mode of illumination of a focused ground glass holocamera of the type delivered to RPL under the earlier liquid rocket engine program (Contract F04611-69-C-0015). A summary of the different resolution tests is presented in Table III. For these tests, resolution was taken or defined to be the minimum discernable bar width of the 1951 pattern. The results are the best of several different tests. In general, the 75° scene-reference beam angle holograms gave the highest resolutions.

To learn about the effects of a wavelength change between the recording and reconstructing steps, a set of holograms was also recorded with a helium-neon laser and reconstructed with the same laser. The results are shown in Table IV. Comparison with the ruby-helium neon lasers results in Table III shows only a slight improvement in resolution with non-lens-assisted holography when there is no change in wavelength between recording and reconstruction.

The second row of Table IV shows a variation in reference beam arrangement, namely, the effect of the addition of a second reference beam. Comparison with the one reference beam case (upper row) shows a 20% resolution improvement for the diffuse illumination condition.

Table III

SUMMARY OF RESOLUTION OF
NON-LENS-ASSISTED "RUBY--He-Ne"
HOLOGRAMS MADE IN FIGURE 15 APPARATUS*,+

θ Scene-Reference Angle, Degrees	Collimated Scene Beam		Diffuse Rear Illumination			
	Scene to Reference Ratio 1:1	Scene to Reference Ratio 1:10	Diffuser Pair Just Behind Res. Target	Diffusers 3 1/2" Behind Res. Target	Diffusers Focused To Infinity	Diffusers Focused Onto Hologram
30°	3.1μ	3.1μ	7μ	7μ	6.2μ	6μ
45°	2.7	3.5	7	7	9.8	5.5
60°	3.5	3.1	8	6	6.2	6.2
75°	3.1	2.5	4.5	5.5	-	5.5
90°	3.9	3.9	8	8	6.2	8.8

* Scene was Air Force 1951 Resolution Target 6 inches in front of hologram.

\+ Reconstructed by reverse reference technique. The reconstructed real image of the chart was expanded with a microscope to limits.

Table IV

SUMMARY OF RESOLUTION OF HELIUM-NEON--HELIUM-NEON
HOLOGRAMS MADE IN FIGURE 15 APPARATUS

Scene-Reference Beam Angle (degrees)	Collimated Scene Beam: Scene-Reference (1:10 Ratio)	Diffuse Rear Illumination: Diffuser Just Behind Resolution Target	
		Diffuser Pair	Opal Glass
75°	2	6	5
75° & 47°	2	4.5	4

Lens-Assisted Holography

In this approach to high resolution, a set of 1:1 imaging lenses is used to relay the object onto the hologram. The technique is subtle in that numerical aperture is provided by the lenses, while the hologram now records the phase and amplitude information (i.e., 3-D information) about each point of the object over a small portion of its surface. This is contrasted to conventional (non-lens-assisted) holography where each point of an object is spread over the entire hologram.

The assisting lenses form or provide resolution, it being remembered that resolution of any optical apparatus is simply

$$R = \frac{\lambda}{2(N.A.)} \quad ,$$

where N.A. = n sin i, and i is the half-angle subtended by a point on the object (or a particle and the aperture of the lens or recording system).

The holographic concept which is being employed or exploited is the fact that the aberrations introduced by the focusing lenses can be subtracted away when the hologram is reconstructed back through the recording lenses by the reverse reference beam technique. The lenses then give, in principle, a perfect reconstruction, limited in resolution by their own numerical aperture. To work in this manner, the lens and hologram are considered as a single optical element. They are mounted rigidly together. One arrangement of the two can be seen in Figure 5.*

Initial tests were conducted with a set of antireflection coated simple plano-convex lenses which had enough aberrations to preclude a sharp focus.

As with the non-lens-assisted tests, test holograms were recorded for both collimated and diffuse types of illumination. Holograms were recorded with both ruby and helium-neon lasers.

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* In this arrangement, the hologram, a 4 x 5 inch glass plate, was held kinematically by machinist pins pressed into an aluminum plate. After exposure, the plate could be chemically developed. When dried, it was replaced (precisely) in the holder for the reconstruction step described later.

The optical arrangement is shown in Figure 16. The hologram holder and focusing lenses were rigidly connected. The resolution chart (or object) was not at the conjugate 1:1 image position of the hologram. Instead, it was purposefully put 3 centimeters out of focus, sufficient so that the image of the hologram under diffuse illumination was blurred.

For reconstruction, the lens-kinematic plate holder with developed hologram was set up as a unit before the collimated beam from a 60 milliwatt helium-neon laser, as shown schematically in Figure 17, and actually in Figure 18. The hologram was reconstructed by the "reverse reference beam technique." By this method, the hologram produces a counter-propagating version of the wave front originally incident upon it. The secret, as noted above, is that all lens aberrations are removed when the reconstructed counter-propagating wave front passed back through the lenses. Beyond the lenses, a real (aerial) image was formed at the original image position. This image could be examined microscopically, as seen in Figures 17 and 18.

Initial test results were encouraging. The results are presented in Table V. In general, resolutions approaching the ultimate were achieved when there was no change in wavelength between the recording and reconstructing steps. For holograms recorded with a ruby laser and reconstructed with a helium-neon laser, the reconstructions were no better than the non-lens-assisted holograms, when the scene was diffusely illuminated. For collimated illumination, there was a clear factor of two improvement in resolution, provided the focusing lenses were achromats. The lens-assisted holographic technique was adopted for the rest of the program, with the recommendation that future work be done with lasers in which there is no change in wavelength. A candidate laser is doubled YAG which generates single and multiple Q-switched pulses of green light (0.53 microns). Unlike ruby, this laser can operate continuously in the green where the eye has good sensitivity. Holograms would be reconstructed with the continuous version. The shorter wavelength would give even better resolution.

Since the resolution results were higher than any that had been achieved to date, a paper was prepared for publication in Applied Optics.*

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* R. A. Briones, L. O. Heflinger, and R. F. Wuerker, "Holographic Microscopy," Applied Optics, April 1978 (reproduced in Appendix III).

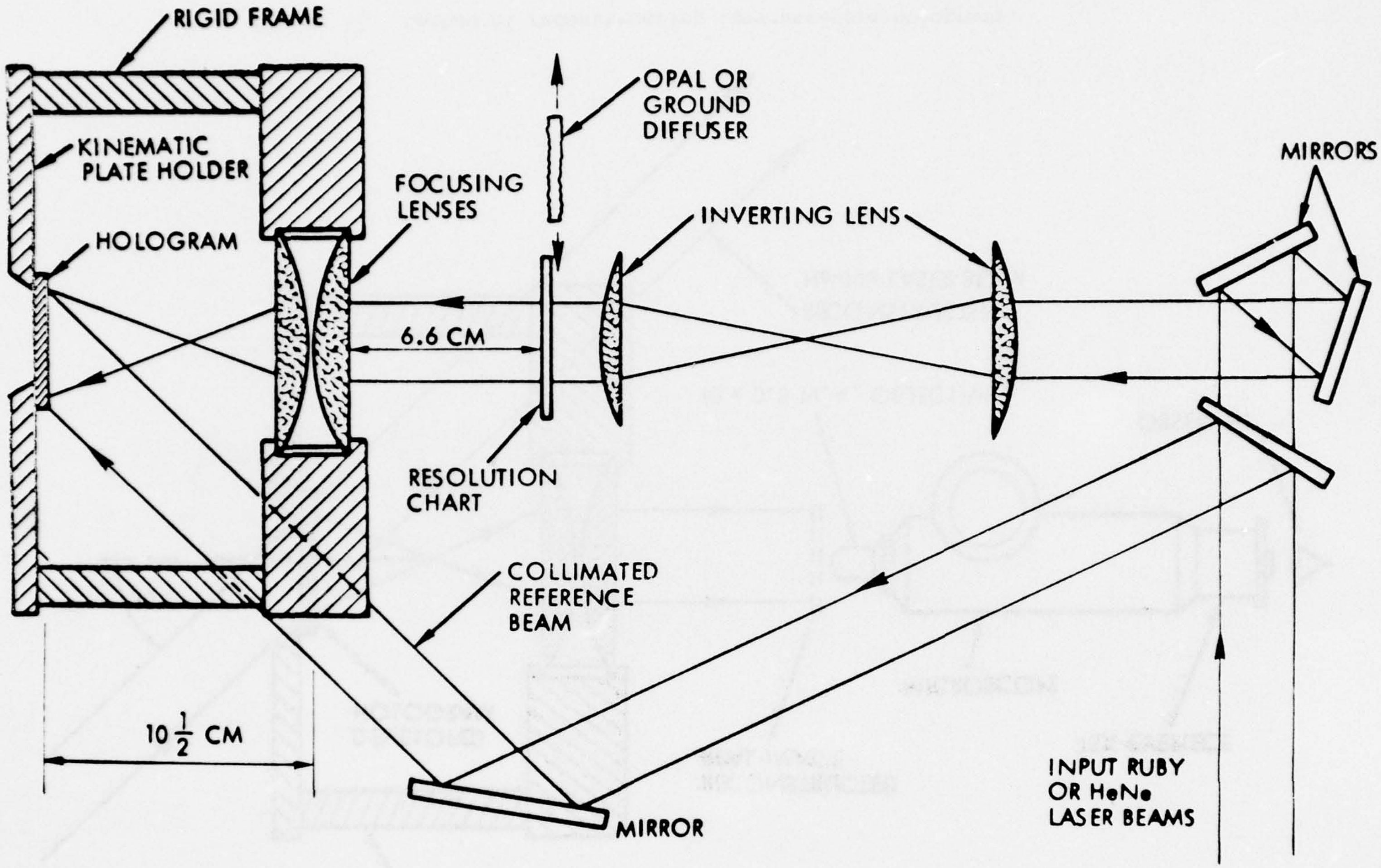

Figure 16. Schematic of two-beam lens-assisted holographic arrangement.

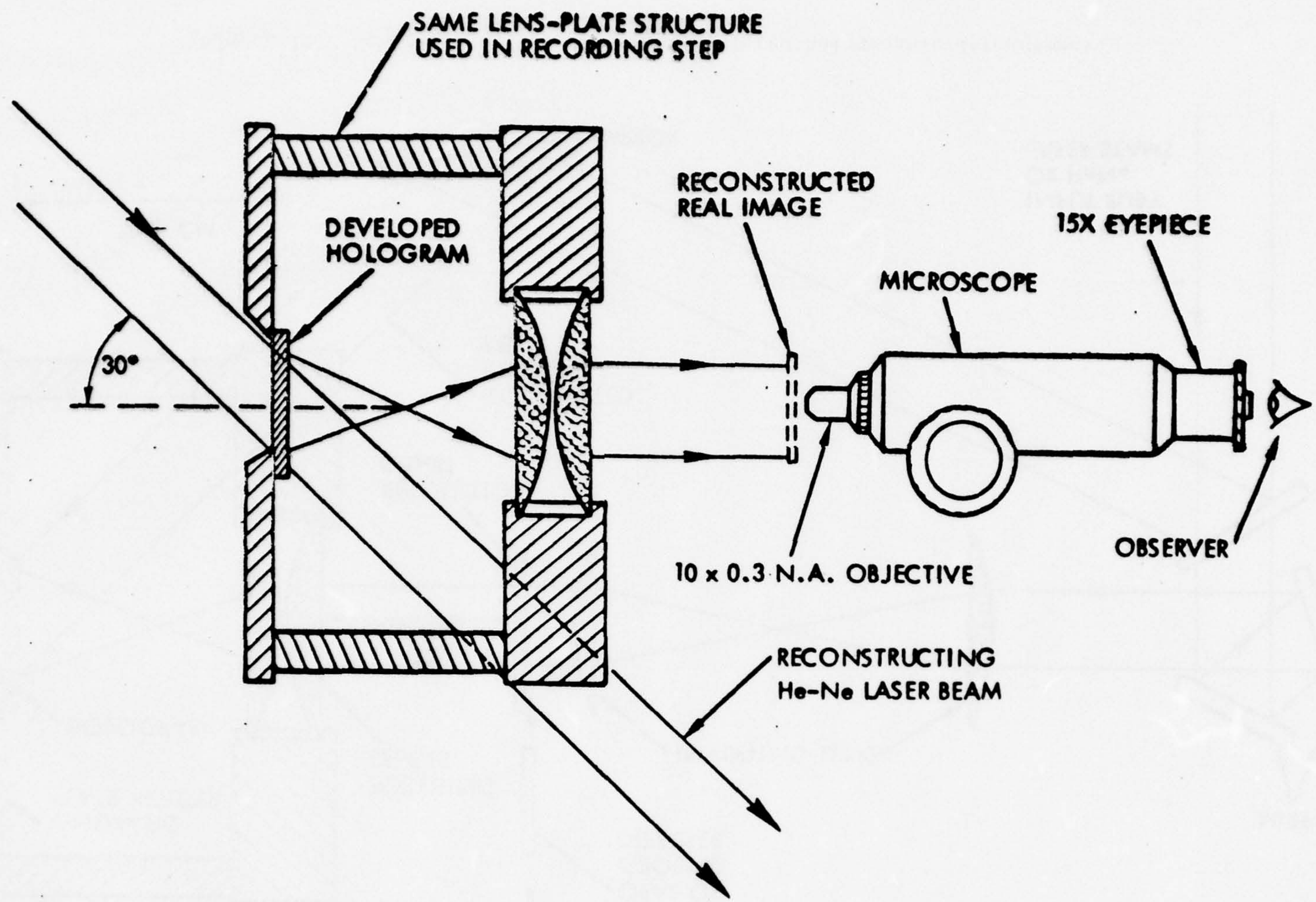

Figure 17. Method of reconstructing lens-assisted holograms.

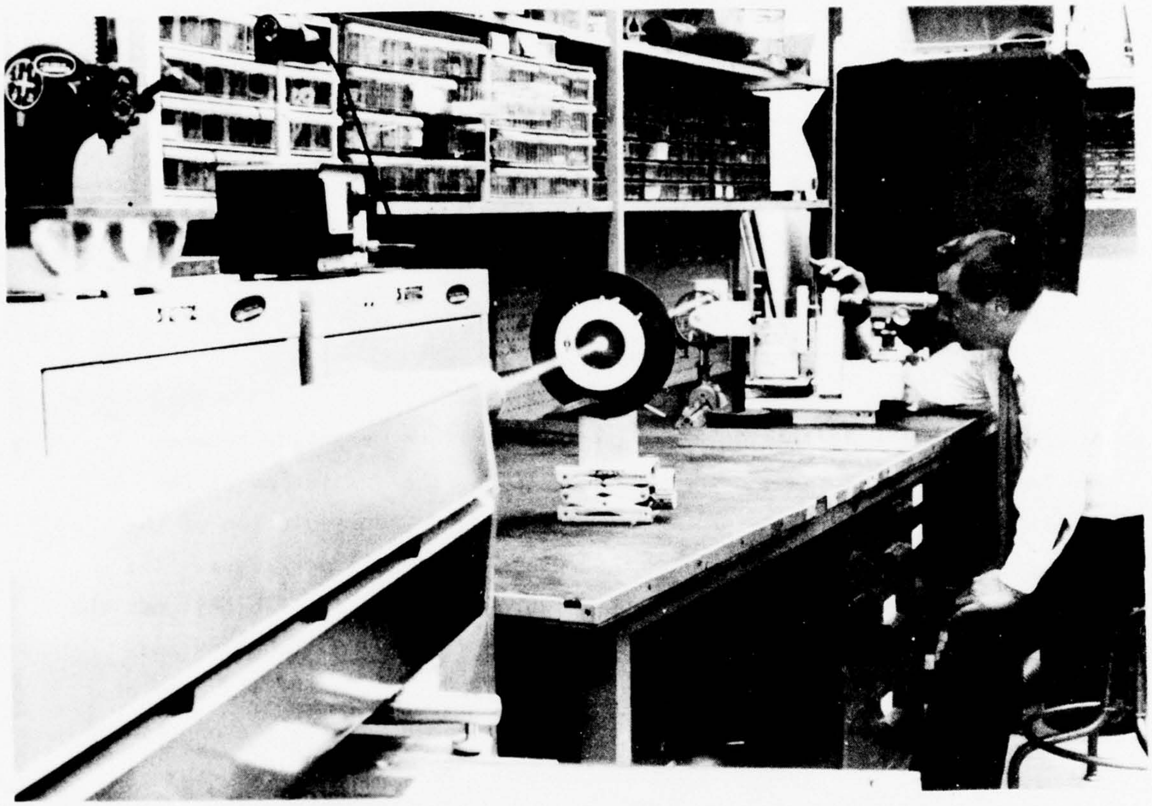

Figure 18. Photograph of method of reconstructing lens-assisted holograms.

Table V

LENS-ASSISTED

SUMMARY OF RESOLUTION OF PRELIMINARY HOLOGRAMS
MADE IN FIGURE 2 APPARATUS

Recording Laser	Reference Beam	Scene Illumination: Collimated	Scene Illumination: Double Diffuser	Scene Illumination: Opal Glass
Ruby	30°	$1 < 2\mu$	6μ	$7\ \mu$
Helium-Neon	30	$\sim 1\mu$	3	3.5
Helium-Neon	30° & 45°	-	-	2

In working up the Applied Optics paper, comparisons were made between the resolution of the hologram reconstructions, the resolution of the examining microscope, and the differences between the resolution of the microscope when it is using incoherent white light or laser light. The paper is reproduced in Appendix III. Figure 8 of this paper highlights the lens-assisted development by showing both the three-dimensionality and high ($\sim 1\mu$) resolution of the technique.* Appendix IV carries a copy of the companion paper which was submitted simultaneously with the one for this contract. This second paper tells about the earlier use of the technique to record movies of marine plankton. The movies were recorded with a 100 pulse/second (0.535μ) xenon laser of 4 microsecond duration. The xenon laser was too weak and too long in duration for recording propellant holograms.

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* In this example (Figure 8, Appendix III), carbonyl iron powder ($< 4\mu$ diameter) was dusted on one side of the 1.5 mm optically thick resolution chart. Images of these particles can be seen in the right pair of pictures. In this picture, the resolution chart is highly out of focus. In the left picture, the resolution chart is in sharp focus, while the particles are completely out of focus (not seen). Particles as small as one micron could be seen. Similar holograms were also recorded with the resolution chart dusted with transparent latex spheres ($\sim 2\mu$ diameter). These could be seen in the reconstruction, but just barely.

Tests were also conducted with the Figure 16 apparatus on the effects of 0.8 inch thick windows on the resolution of the reconstructions. It was found that the windows did not affect the resolution for the collimated holograms, but did for the diffuse holograms (a factor of about 2). Their effects could be cancelled by inclusion of the windows in the reconstruction step.

Special thin emulsions (15 micron thick gelatin) gave no gain in resolution over normal 30 micron thick gelatin emulsions. Unhypoed plates also gave no improvement in resolution.

Phase I Combustion Holograms

Holograms were recorded of propellants at 500 lbs/in^2 using the focused image holographic technique. The apparatus was already shown in Figures 3, 4, 5, 6, 7, 8, 9, and 10. Collimated, diffuse, and scattered light (dark field) types of illumination were tried. For the collimated type holograms, a Wratten #70 and a Neutral Density filter were placed in the camera shutter (Syncho Compur with tested 5 millisec maximum speed). These reduced the flame light to below the film fogging levels. The ND filter also reduced the laser scene beam to below (1/4) the reference beam intensity. For diffuse and scattered light recordings, the ND filter was removed. Metalized propellants now fogged the film. A narrow band (0.39 inch thick) filter was added. In conjunction with the 5 milliseconds shutter duration, it was sufficient to reduce the film fogging effect below the laser exposure. A photomicrograph of the reconstruction of the resolution chart taken through the 0.8 inch thick fused quartz window and 0.39 inch thick narrow band filter is shown in Appendix III (see Figure 12). The resolution was not as good as with the filter removed. The smallest bars of the 1951 chart were resolved (these are 2.2 microns wide).

Examples of the reconstruction of a collimated hologram of the combustion of MS-23 fuel under collimated light conditions is included in Appendix III (see Figures 9-12). Each picture is of the same holographic reconstruction and is at higher and higher magnifications. The last picture of the sequence (i.e., Appendix III, Figure 12) represents verification of a major program milestone, namely, resolution in a combustion environment of better than 3 microns.

In general, it was found that for collimated illumination, the thermal cells strongly refracted the laser light, with the result that particles were hidden. One could see particles only inside the uniform regions of these cells, but not near the boundaries.

For forward scattered light illumination, i.e., where the collimated scene light was blocked at the focus of the assisting lenses, the situation was even more severe. The scattering of laser light by particles was completely masked by the scattering by thermal cells. Particles, as a result, could not be seen or identified by forward light scattering. This mode of recording was abandoned.

The diffuse light holograms showed minimal refractive effects. Particles could be seen and identified. Unfortunately, the diffuse light ruby laser holograms were not as high in resolution when rconstructed with a helium-neon laser. Later in the Phase II part of the program, a "moving diffuser" scheme was discovered as a way of restoring some of the lost resolution of the diffuse light holograms.

An example of the reconstruction of a diffuse light hologram is presented in Figure 19. It was of MX-70 fuel burning at 1000 lbs/in^2. Particle size can be estimated from the burned 220 micron diameter ignitor wire.

The program through Phase I was reviewed at the Rocket Propulsion Laboratory, December 20, 1976. Following the presentation or formal program review, the attendees were invited to view some selected combustion holograms. These were reconstructed in the lens-assisted holder with a RPL-provided helium-neon laser. Any image could be viewed with the eyes or magnified with a pocket magnifier or microscope. At that time, it was decided to continue the program through Phase II.

Figure 19. Photograph of reconstruction of diffuse light hologram of combustion of 1/4 x 1/8 x 1/16 inch piece of MX-70 solid rocket fuel burning at 1000 lbs/in^2 chamber pressure.

IV. PHASE II

The Phase I effort demonstrated the feasibility of recording holograms of the combustion of small 1/4 x 1/8 x 1/16 inch solid propellant samples at high pressures (< 1000 lbs/in^2). A ruby laser "focused light" holographic system yielded, under collimated illumination conditions, holograms of non-metallized propellants (MS 23) which reconstructed (with a helium-neon laser) to $\lesssim$ 3 micron resolutions. Collimated illumination holograms showed light refractive effects due to thermal cells. In some cases (MX-70 propellant), the cells were numerous enough to make particle identification nearly impossible. The thermal cell effects precluded any type of forward scattered light holography. Diffuse light holograms were not as subject to thermal cell refractive effects due to the fact that diffusers provided a continuum of illumination, with the result that thermal cells were averaged.

Metallized fuel holograms were, in addition, characterized in their reconstructions by regions of opacity. This was thought to be a holographic, rather than a particle density, effect.*

The Phase II effort was concerned with the further refinement of the holographic techniques initiated under Phase I. The primary goals of the Phase II effort were:

- particle velocity
    - by multiple exposure holography,
- flame density gradients
    - by holographic interferometry,
- propellant surface characteristics
    - by reflected light holography,

and

- particle size distributions
    - by analysis of holographic images.

---

* Later in the Phase II program, this suspicion was verified. Holograms were recorded with order of magnitude shorter pulse durations ($\sim$ 8 nanoseconds). The reconstructions were relatively clear of opacities, which verified that the opacities were, in fact, "time averaged (transmission) interference fringes."

In addition, the authors were to more systematically record different Air Force propellants (see Table I).

Suffice it to say, all of these tasks were investigated and were solved to various degrees of satisfaction. The Phase II effort is summarized in a paper which was presented by one of the authors (R. A. Briones) at the JANNAF Combusion Meeting (August 18, 1977, at Colorado Springs, Colorado). This paper is reproduced in Appendix V. The paper includes, in addition, the Phase I development of the lens-assisted method. Examples of the recording of different propellants are a part of the paper. This paper is the real program summary. It should be read carefully. Other aspects and details of the Phase II effort are summarized below.

Short Pulse Recording

As noted above, holograms of metallized fuels recorded with 50 nanosecond Q-switched pulses showed reconstructions characterized by opacities. Examples of this effect for NB-122 propellant are seen in Appendix V, Figure 15. To check whether this was a particle density effect or a holographic effect, the laser pulse duration was reduced to ~ 10 nanoseconds with a pulse chopper.* Recordings with the pulse chopper were far more transparent (see Appendix V, Figures 7 and 8). Pulse chopping, however, had the adverse feature of reducing the total laser energy to almost insufficient amounts, needed to properly expose the hologram and compete with flame light fogging.

So important were short pulses to the recording of holograms that a block of time was spent trying to reduce the laser pulse to even shorter durations by mode-locking techniques. Although mode-locking a ruby laser had been successful nearly seven years ago,** with a D.D.I. dye cell, attempts to

* The pulse chopper was a piece of laboratory equipment which had been built by the authors under an earlier program. Basically, the output of the laser is directed into a laser-triggered spark gap filled with a 50/50 mixture of argon and nitrogen. The beginning of the Q switch pulse short-circuits the gap. This launches an electrical pulse of 10 nanosecond duration and voltage equal to half-wave voltage of a Pockel cell, down a coax line. When the pulse hits the end of the line, the cell opens and light of a duration equal to the electrical pulse duration is transmitted. A pulse chopper was included with the Phase III laser.

** Earlier work produced a mode-locked train of 2 nanosecond pulses separated from one another by 7 nanoseconds (the cavity transit time).

repeat these earlier results failed. New or fresh dye was ordered from the manufacturer; even this would not yield mode-locked performance. The mode locking had to be abandoned for lack of time and other program priorities.

Reflected Light Holograms

Reflected light holography of the burning surface used the angled viewing window (see Figure 8) that was a part of the combustion bomb. This meant cutting the fuel surfaces on a bias. Initially, the focused image technique was tried. These, however, proved too difficult in interpretation. Either it was a combination of astigmatism (due to the 10% wavelength shift on reconstruction) or the fact that the propellants were somewhat translucent to ruby laser light. The images just could not be interpreted, even of non-burning samples. The focused image reflected light holograms were abandoned. Instead, non-lens-assisted holograms were tried. The optical arrangement is shown in Appendix V, Figure 19. Not only could the surface be seen, but, in addition, the particles could be seen by their own scattering of the laser light. Examples of these recordings are seen in Appendix V, Figures 20 and 21. Visualization of particles by scattering was a surprise, particularly since the forward light scattering attempts had failed. Apparently, the thermal cells did not refract light beyond the forward scattering angles, leaving the particles free of such effects.

Rotating Screen

During the analyses of the reflected light holograms, a scheme was discovered by one of the authors (R. A. Briones) for improving the resolution of the hologram reconstructions. It consists basically of projecting the aerial holographic image on a screen and then moving the screen at rates greater than eye flicker rate. The method seems to suppress speckle noise. In addition, it made viewing the reconstruction easier. One version is shown in the Appendix V summary (see Figure 11). In this version, the image is being relayed by a first microscope objective onto a rotating screen. The secondary image is being viewed by a second microscope objective. The screen (a piece of mylar) was attached to a rotating disk. This arrangment was not as satisfying as the one in which the screen passes through the primary holographic image. The microscope views the

moving screen. However, in this latter arrangement, one has to be careful that the screen does not flutter beyond the microscope's focal plane. Attempts were made to write up the rotating diffuser technique as a paper for publication; however, the proof of claimed improvement proved too hard to document via pictures. The preliminary efforts are presented in Appendix VIII. The effort was considered a diversion, and had to be abandoned.

Hologram Analysis

The rotating viewing screen was used in the careful analysis of a small 1/2 cubic millimeter portion of the image reconstructed from a diffuse light hologram of MX-70 propellant. The volume is outlined in Appendix V, Figure 9. It was 0.66 millimeter above the burning surface and extended from the mid-plane out for a distance of 12.7 millimeters. Every particle in this volume was located, assigned relative Cartesian coordinates, and sized (assigned an effective diameter). The analysis was carried out with the rotating screen technique shown in Appendix V, Figure 11. In this picture, one can see the dial indicators and travelling eyepiece that measured, respectively, the particle positions and size. Within the chosen volume, 569 particles were found. They ranged in size from 85μ diameter (largest) to 2.5 microns (smallest). The latter were below the 6.5 microns granularity size (due to diffuse light recording and reconstruction with a helium-neon laser). It is claimed by the authors that the rotating diffuser made or effected the improvement in resolution!? The counting was manual and quite laborious. It took 8 days! The data are reproduced in Appendix VI. The data were plotted as a particle size distribution to demonstrate that holography could, in fact, give quantitative information about solid propellant combustion.* The resulting particle distribution is presented in Appendix V, Figure 10.

Double Exposure Holography

Double exposure techniques were next investigated as a way of determining particle velocities. In addition, the techniques of holographic interferometry were considered. The tests were begun while recording reflected light holograms; none of these proved anything conclusive about

* This data was one of the principal highlights of a talk given by the authors at an AFOSR Meeting (March 11, 1977), Lancaster, California.

the ability to determine velocity from a double exposure image. One could not correlate particle images. Transmission images proved no better; one could not tell which was the second position of a particle. The tests, however, did lead to some good differential holographic interferograms, examples of which are shown in Appendix V, Figure 16. No fringes could be seen around the individual particles, indicating that they were probably in thermal equilibrium.

Conventional interferograms could also be recorded, only for the collimated illumination condition. The first exposure was taken prior to combustion, and the second exposure during combustion. Examples are seen in Appendix V, Figures 12 and 13. Puzzling still is the fact that the diffuse light holograms showed no fringes. Reasons for the difference between the two have not been settled.

To eliminate the confusion about the double exposure holograms, a new holocamera was constructed. It is shown schematically in Appendix V, Figure 17.+ Two images are recorded on the same plate, except that because of the different reference beams, the images can be separately reconstructed. Examples of two different images taken from the same hologram are presented in Figure 18. Direct viewing is much better, since the pictures can be rapidly blinked back and forth. One sees the images jump. By measuring the distance and dividing by the known time separation between the two laser pulses, one can compute the velocity and direction of the different particles. For example, MX-70 propellant at 500 psi pressure showed particles moving at a speed of 6 meters/second. The double reference beam holocamera demonstrated a new technique for determining particle velocities.

Tests with the double exposure double reference beam method ended the Phase II program.

The Phase II effort was reviewed by the contracting officer May 19, 1977, At that time, it was decided to continue with the Phase III effort; to reconstruct the existing RPL laser* and to package a holocamera to record double reference beam tranmsision holograms as well as reflected light

\+ It is also discussed in Appendix IX, which is the writeup of a patent disclosure.

* This laser was delivered by the authors under an earlier program. It is described in R. F. Wuerker, "Instruction Manual for Ruby Laser Holographic Illuminator," Contract F04611-69-C-0015, February 1970.

holograms. The laser was to be modified for multiple pulse capability. In addition, pulse chopping both pulses was to be investigated, a feat that had not yet been achieved. In summary, the Phase II effort showed that:

- Particle velocities could be determined from double exposure double reference beam holograms.
- Thermal cells could be recorded by conventional transmission (collimated) double exposure holographic interferograms.
- Propellant surfaces could be recorded by reflected light non-lens-assisted techniques.
  - Surface detail was poor, due either to the translucent nature of the surface or because it was liquid.
  - Particles could be seen by their scattering of laser light.
- Qualitative information about particle size and size distribution could be realized from careful analysis of holograms.
  - Rotating a viewing screen, through the aerial image, improved resolution and viewing.

V. PHASE III

Background

Phases I and II of the present contract demonstrated the feasibility and importance of recording holograms of the combustion of solid rocket propellants in a small high pressure combustion bomb.

In addition, four new facets apropos both holography and the recording of combustion of small particulate were discovered during the course of the experimental effort. These include:

- The use of "assisting" lenses to increase the resolution of a hologram.
  - Resolution increased better than a factor of two over conventional holography when there was no change in wavelength on reconstruction.
  - Collimated transmission illumination gives highest (one micron) resolutions, even with 10% change in reconstruction wavelength.
- The need for diffuse rear illumination to visualize particles in the presence of small (half millimeter) thermal cells (characteristic of solid propellant combustion).
  - Particles become hidden in thermal cells when the scene is illuminated only in transmission by collimated illumination.
- The need for extremely short (10 nanosecond or less) laser pulses to record metallized propellants.
  - Gas density changes result in "time-averaged fringes" when holograms are recorded with 50 nanosecond pulses.
- Rapid double exposure-separate image holography.
  - Requires a holocamera with separate reference beams.
  - Images can be separately reconstructed.
  - Such images yield particle velocities without confusion.

Details are summarized in the Appendix V review paper.*

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* D. George, R. A. Briones, and R. F. Wuerker, "Holography of Solid Propellant Combustion," SPIE Meeting, San Diego, California, August 25-26, 1977.

Holocamera

The Phase I and II results led to the design of a new holocamera. The first version is schematically diagrammed in Figure 20. Further details are given in Appendix X. The new design differs from earlier holocameras primarily by the incorporation of a pair of assisting lenses and by the addition of a second independent reference beam.

The assisting lenses, as seen earlier, make possible the achievement of high resolutions when holograms are reconstructed by the reverse reference beam technique.* These relay lenses provide the numerical aperture needed to achieve high resolution. They need only be simple plano-convex lenses; however, achromats have been shown to be best when there is a change in wavelength on reconstruction.

With the two independent reference beam paths, two separately reconstructed images can be recorded on top of one another (i.e., on the same plate). The beam splitters (that provide the reference beam) are arranged so that they reflect only vertically- or horizontally-polarized light, respectively. This is achieved by tipping the beam splitters to the Brewster angle.+ As a result, each reflects only the light (15%) whose electric vector is parallel to the plane of the reflecting surface; neither reflects any of the orthogonally-polarized light. For the Figure 20 arrangement, the reference beam directions are chosen by the polarization direction of the input laser pulses.

As a result, two independent separately reconstructable images are recorded on the same plate. Holograms recorded on a rapid double exposure basis will show, on reconstruction, the particle field at two different intervals of time. Particle motions can be followed if the pulses are separated by time short enough ($\sim$ 10 microseconds) so that the particles have moved not more than five or ten diameters. Particle velocities follow naturally from such unique recordings.

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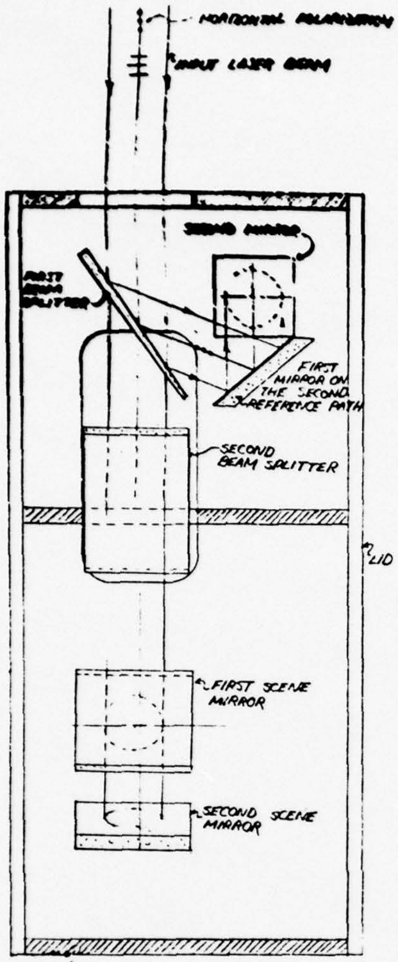
* Ibid (see in particular Figure 2).

\+ At the Brewster's angle, no polarized light is reflected from a glass surface whose direction of vibration is in the plane determined by the direction of propagation and the surface normal. The effect is explained in the holocamera instruction manual (see R. F. Wuerker and R. A. Briones, "Operation Manual for Lens-Assisted Multiple Holocamera with Reflected Light Option," December, 1977); see Appendix III.



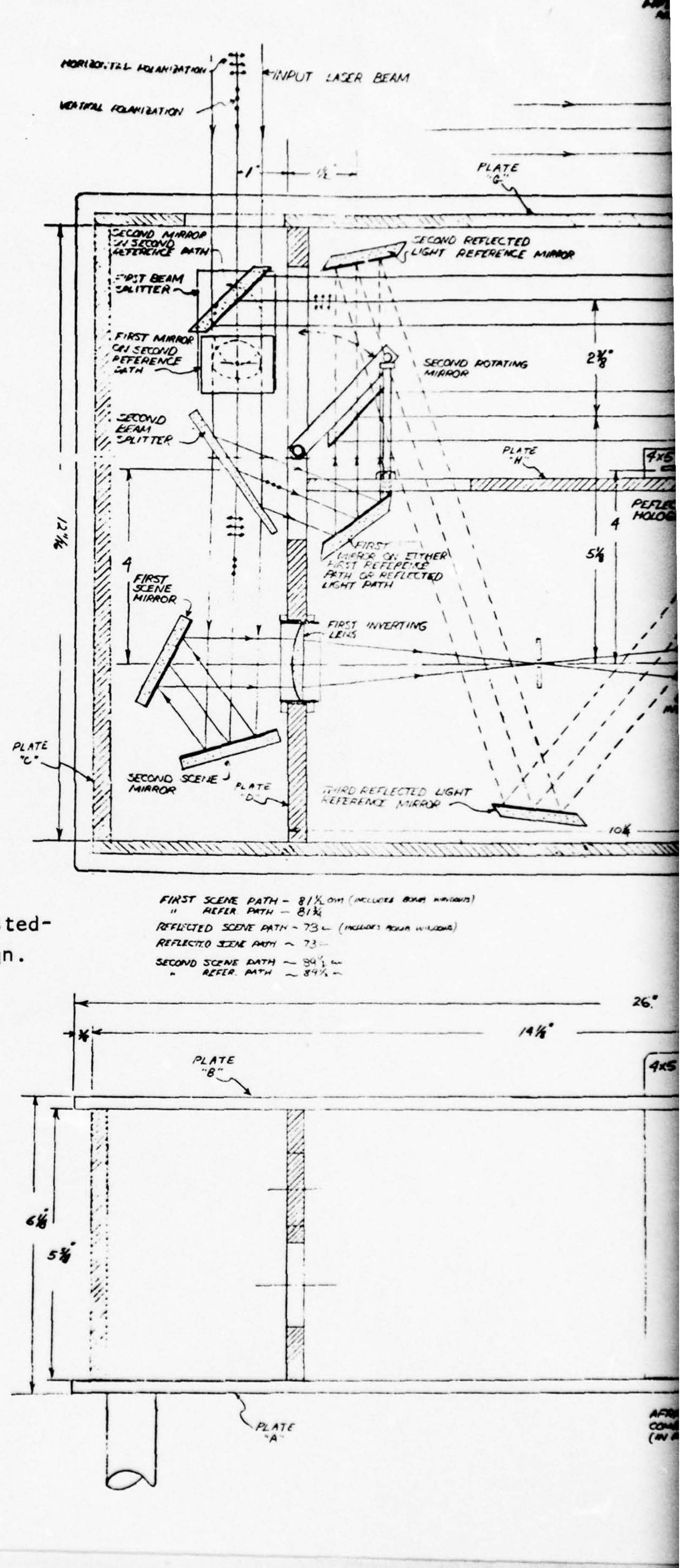
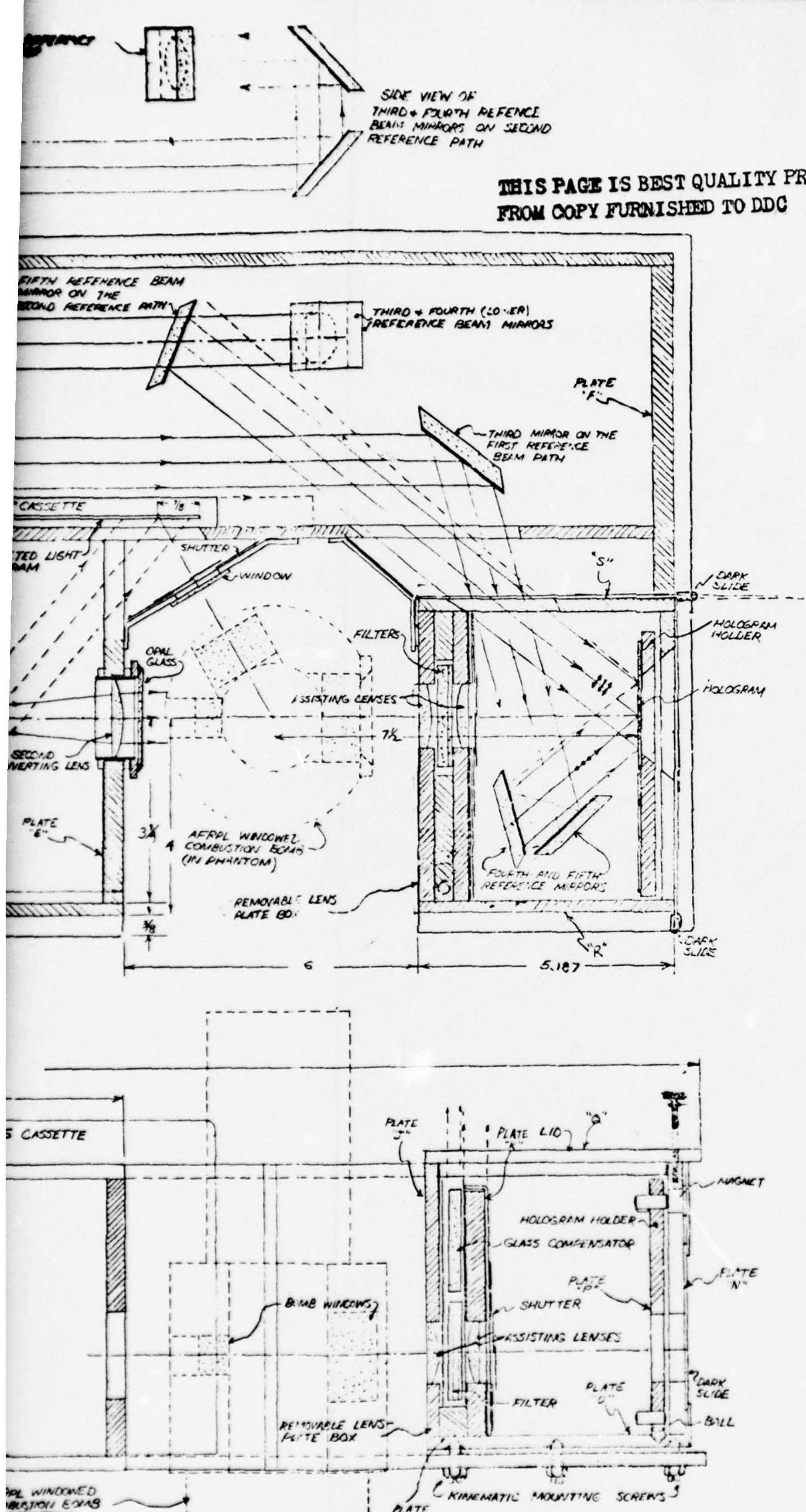


Figure 20. Double Reference Beam-Lens Assisted-High Resolution Holocamera Design.



RPL HOLOCAMERA

The new holocamera is completely passive. It can be used with any linearly polarized solid state laser such as ruby, doubled ruby, doubled YAG, etc., whose output pulse polarization can be rotated with an external electronic half wave plate such as a Kerr cell or a Pockel cell.

The new holocamera requires only a laser system that emits two orthogonally-polarized output pulses. The first pulse is reflected by the first beam splitter. None of it is reflected by the second beam splitter. Most of the light (72%) passes through the splitter into the scene beam portion of the holocamera. The holocamera records a hologram of the scene with a reference beam of positive angle with respect to the scene direction. The second orthogonally-polarized pulse is not reflected by the first beam splitter. Only the second Brewster angle splitter reflects a 15% portion of light and directs it along the second reference beam path (corresponding to the negative angle reference beam). The second hologram is recorded superpositioned over the first on the same photosensitive plate. After development, the two images can be separately reconstructed by re-illumination from the two different reference beam directions.

The holocamera can be used as a conventional holocamera by simply not rotating the polarization of the second pulse. It will then record conventional rapid double exposure holograms and holographic interferograms.

The reference beam mirrors are located so that the two reference beams are both spatially and temporally matched. The scene beam is similarly matched. Temporal matching permits recording of holograms with lasers of low temporal coherence. Spatial matching accommodates lasers of low spatial coherence (such as a Q-switched ruby laser). The two mirrors and the inverting lenses in the scene arm of the new holocamera were needed to spatially match the scene beam to both reference beams.

The scene is placed between the inverting lenses and the assisting lenses. Events are transilluminated by collimated scene light. This mode of illumination gives highest resolution (particularly for ruby holograms reconstructed with a helium-neon laser of 10% shorter wavelength). Diffuse illumination will be achieved by inserting a piece of ground glass just after the last inverting lens (or anywhere behind the subject).

The assisting lenses provide the numerical aperture needed for microscopic resolutions. Narrow band filters (transparent to the laser light, but reflecting at all other wavelengths) are placed between the two assisting lenses. These filters in concert with the mechanical shutter reduce the flame light to below the laser light levels.

The assisting lenses and the hologram plate holder are fixed rigidly together so that the combination is considered to be a single optical element. The two are mounted so that they can be withdrawn as a unit for the purposes of loading fresh plates or for reconstructing already processed holograms.

The holocamera also provides a reflected light option. This is also diagrammed in Figure 20. For reflected light recording, the second reference beam is re-routed and used to record non-lens-assisted reflected light holograms. Since the first reference beam is undisturbed, it will be possible to make both a simultaneous transmission hologram and reflected light holograms of the same event. For such recordings, the hologram should be further covered with sheet polarizers to minimize fogging due to the non-used orthogonal polarized scene light.

In summary, the holocamera shown in Figure 20 and built under Phase Phase III has the following features:

- Superpositioned, but separately reconstructable, holograms.
  - For recording 3-D particle phenomena at two separate times.
- High resolution.
  - 2 microns for collimated illumination and for helium-neon laser reconstruction of ruby laser holograms.
  - 7 microns resolution for diffuse light holograms, ruby laser recorded and helium-neon reconstructed.
- Non-lens-assisted reflected light option
  - 10 micron resolution
  - Particles subject to holography's motion condition, "To be recorded, optical path must not change by more than one-tenth wave."

- Six-inch diameter scene volume, to accommodate the RPL combustion bomb (see Figures 8 and 9).
- Holograms are recorded on 4 x 5 glass plates.
- The assisting lenses and plate holder are a single unit which can be easily removed from the holocamera for purposes of reloading with a new plate or for reconstructing the hologram.
  - A pair of solenoid actuated shutters are a part of this assembly and will also serve to fire the laser.

Ruby Laser Illuminator

The laser which was originally delivered to RPL forcrecording holograms of liquid rocket propellants was rebuilt.*,+ The rearrangement of components in the laser is shown in Figure 21. Inspection will show that the same laser chest was used, and consists internally of a ruby laser oscillator and a ruby laser amplifier. Changes which were made include the permanent addition of two Kerr cells to the oscillator cavity. These are for the purpose of rapid double pulsing the output, with pulses separated anywhere between 1 and 400 microseconds. With two Kerr cells in the laser, the total cavity reflectivity must be increased. This was done by replacing the single element sapphire etalon by a double quartz etalon. The new oscillator will produce two pulses of nominally 1/8 joule content each and typically 50 nanoseconds in duration. Such pulses are turned by a pair of prisms (a part of the original apparatus) and passed through the amplifier rod. The amplifier has a single pass gain of three.

A small Kerr cell was placed at the output of the amplifier. It is for the purpose of rotating the plane of polatization of one of the double pulses from the oscillator. The output of the entire assembly as described is two nominally 3/8 joule, 50 nanosecond each, orthogonally-polarized ruby laser pulses. Such emission is required to record separately reconstructable holograms in the Figure 20 holocamera.

The laser is also capable of generating a single 7 nanosecond pulse by the pulse chopping technique. For this type of pulse generation, a second Kerr cell is placed before the input to the amplifier (see Figure 21).

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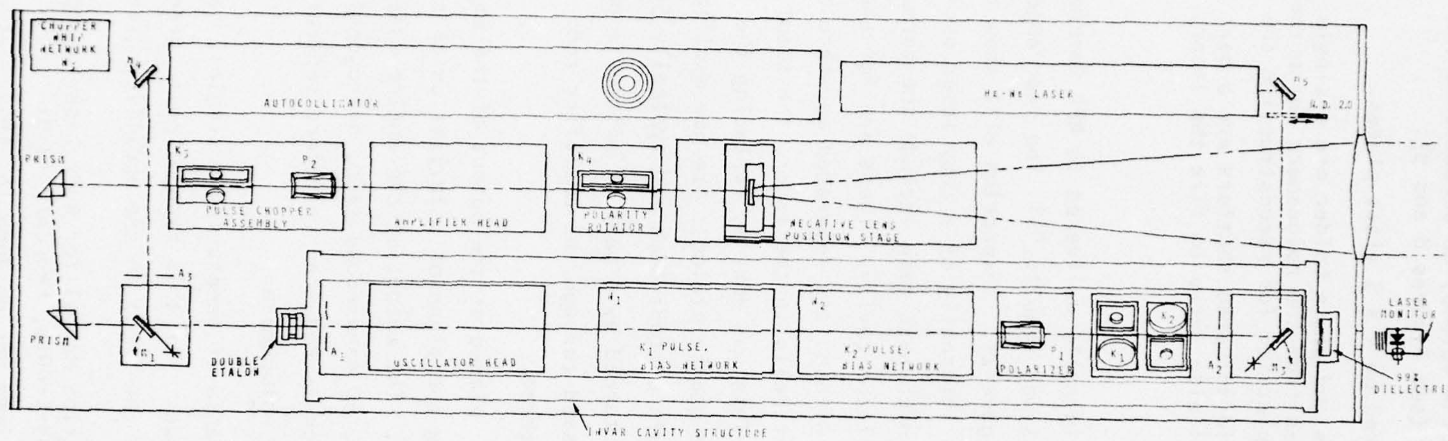
* R. F. Wuerker, "Instruction Manual for Ruby Laser Holographic Illuminator," Contract F04611-69-C-0015, February 1970.

\+ The laser was received from RPL on June 16, 1977. It was shipped back rebuilt to AFRPL on December 21, 1977.



M_1 RETRACTABLE MIRROR FOR AUTOCOLLIMATOR ALIGNMENT
M_2 DELETED
M_3 RETRACTABLE MIRROR FOR BEAM INJECTION
M_4 AUTOCOLLIMATOR TURNING MIRROR (FIXED)
M_5 TURNING MIRROR (FIXED)
A_1, A_2, A_3 1/4" APERTURES
K_1 K_2, #25 KAPPA KERR CELLS
K_3 K_4, #16 KAPPA KERR CELL (CUSTOMIZED)
N_1 N_2 N_3 POTTED ELECTRONIC CIRCUITS

Figure 21. Modified RPL Ruby Laser.

A Glan polarizing prism directs the light from the oscillator into a spark gap which when fired launches a voltage pulse which biases the Kerr cell to the half-wave voltage for a few nanoseconds. Light rotated during the brief energization of the Kerr cell passes through the polarizer to be amplified by the amplifier ruby.

For the pulse chopper to work, the oscillator's output polarization must be rotated through ninety degrees, electrically biasing the Kerr cell.

Since the spark gap can be fired only once, the pulse chopper can be used presently only to record single exposure 10 nanosecond holograms. Multiple exposure pule-chopped holograms are beyond the capability of the present equipment.

The RPL laser was completely rebuilt. New flash lamps were installed; rubies were repolished; end mirrors replaced; Kerr cell rebuilt and others added, as seen above, for the purpose of double pulsing, rotating plane of polarization, and pulse chopping.

In summary, the rebuilt oscillator has the following capabilities:

- Single pulse, Q-switch operation, nominally 50 nanosecond, 1/2 joule.
- Double pulse operation, nominally 50 nanosecond, 1/4 joule pulses.
- Polarization change of second pulse
    - Required for recording separately reconstructable holograms. in the new holocamera (Figure 20).
- Single pulse chopped operation, ∿ 7 nanoseconds, 1/10 joule pulse.

Multiple Pulse Chopping Effort

Effort was also spent at the beginning of Phase III on the problem of pulse chopping both of the ∿ 50 nanosecond double pulses from the TRW Q-switched ruby laser.

Laser triggered spark gaps can be fired only once in a millisecond period due to the ionization of the gap. A scheme for pulse chopping two Q-switched laser pulses would greatly enhance the usefulness of the new laser holographic system. For this reason, effort was spent on the double pulsing problem.*

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* In the present spark gap pulse chopper, the total (50 nanosecond) light pulse from the laser is diverted by a polarizing prism (see Figure 21) (Cont'd on next page)

An obvious solution to chopping two laser pulses would include a second laser-triggered spark gap, a second polarizer, and a second electro-optical cell. Such a solution would be unwieldy.

Several possibilities were investigated to no avail. These included:

- A shorter spaced, higher pressure laser-triggered gap.
- Gaps filled with an electron-attracting gas (such as SF_6),

and

- Vacuum gaps.

All had logical foundations. It was argued that the small amount of energy ($\sim$ 20 kV in 100 $\mu\mu$F or 0.02 joules) in the charged cable was barely enough to cause appreciable ionization. It was hoped that as a result the gap could, in fact, recover in times shorter than a millisecond, particularly if electrode ends were moved closer, and some attaching gas was added.

The vacuum gap+ was tried in the belief that metallic ions would come from the electrodes (released by the laser pulse) and would rapidly condense, permitting the gap to be recharged faster than a gas-filled gap.

The vacuum gap fired like the gas-filled gap, but could not recover. The gap continued to conduct for several hundred microseconds after being triggered by the laser. That is to say, like a gas-filled spark gap, the vacuum gap is also filled with thermal ions which kept it conducting.

(Footnote cont'd from previous page)

* into the spark gap. Onset of the laser pulse fires the gap, interconnecting a piece of electrically charged cable with an uncharged cable. A voltage wave is launched of magnitude equal to the half-wave voltage of a Kerr cell. The Kerr cell is connected to the end of the unchanged cable. The cable is terminated in its characteristic impedance. A short high voltage pulse (proportional to the charged cable length) is applied to the Kerr cell. This amount of light is passed through the diverting polarizing prism.

Continuous ionization of the gap prevents charging the cable a second time. Stated another way, the charged cable cannot be recharged until the gap has completely deionized, a time of typically one millisecond.

\+ Achieved simply be evacuating the gas-filled laser-triggered spark gap.

All of these efforts to shorten the recovery time of a laser-triggered spark gap led to our reconsidering vacuum photodiodes.* A quick calculation showed that such diodes should, in fact, be able to discharge or charge a Kerr cell or Pockel cell in times shorter than the ∿ 50 nanosecond laser pulse duration. Photocathodes such as S-1 have sensitivities of ∿ 2 mA/W. Thus, a 1 megawatt laser input should produce ∿ 2000 amperes of saturated photoelectric current! Such a current would discharge a 30 μμF Kerr cell at a rate of

$$\frac{dv}{dt} = \frac{i}{C} = \frac{2000}{30\ \mu\mu F} = 66\ \frac{\text{volts}}{\text{picosecond}} \quad , \tag{1}$$

which, given a 20,000 volt bias, would mean a 0.3 nanosecond discharge time. Even a factor 10 less photocurrent would be adequate!

A photodiode is of interest due to the fact that it is a vacuum device and therefore will not be subject to any deionization effects. Like any vacuum device, it should be rechargeable electrically in microsecond times.

The difficulty with a vacuum photodiode is the space charge law. This law limits the amount of electron current which can be drawn between two parallel plates of area A, separated by a distance X and at a potential of V (volts);

$$i = 2.34\left(\frac{A}{x^2}\right) V^{3/2}\ \mu\text{amperes} \quad . \tag{2}$$

Space-charge-limited values for an FW 4000 diode are presented in Table VI for spacings of 0.6 cm (standard spacing) and 0.3 cm.

The gas filled spark gap in the line pulser was replaced by a FW 4000 photodiode. Currents of ∿ 10 ampere peak could be drawn. To increase the current, a 2500 μμF capacitor was connected to the diode. It was added to keep the voltage across the diode during discharge. Peak currents of 50 amperes were achieved; however, they continued beyond the duration of the laser pulse. It was argued that ions were being liberated and the diode was becoming a gas discharge device.

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* Product of ITT Company. The FW 4000 photodiode has a 3.8 cm diameter (11.3 cm^2 area) photocathode separated from the mesh screen anode by 0.6 cm.

Table VI

SPACE CHARGE LIMITED CURRENTS

For FW 4000 Photodiode

(Photocathode Dia. = 3.8 cm, Area = 11.3 cm^2)

Voltage	Cathode Anode Spacing x = 0.6 cm*	x = 0.3 cm
1,000	2.3	9.3
2,000	6.6	26
5,000	26	104
10,000	73.7	295
15,000	135	541
20,000	208	834
25,000	291	1165
30,000	383	1532

* Standard spacing.

Clearly, a diode of closer spacing was desired. To make a long story short, a diode was taken and its spacing reduced to 0.3 cm (i.e., to one-half), by simply heating the glass envelope to the softening point.

The photodiode survived this rather rough treatment without either losing vacuum or poisoning the photocathode. When connected to a 200 $\mu\mu F$ capacitor, the diode passed a peak current of ~ 40 amperes (30 nano-seconds after irradiation), enough to discharge a Kerr cell. The diode did not conduct electricity after the end of the illuminating pulse. It is now believed that such a diode could be used to pulse chop a ruby laser. Since it is a vacuum device, it will not have recovery problems and will chop each pulse of a double pulsed laser emission.

A patent disclosure has been prepared. It is included in Appendix VII.

More development needs to be made on the vacuum photodiode pulse chopper, before it can be used reliably. Additional tasks include a diode with short spacing (2 millimeters) as well as different (heavier) anode structure. Such developments were beyond the scope of the present effort.

Further development on the photodiode chopper was discontinued.

VI. SUMMARY AND CONCLUSIONS

A lens-assisted transmission holographic apparatus has been successfully used with a ruby laser to record three-dimensional information about the combustion of small propellant samples at high pressures ($\lesssim$ 68 atmospheres). The holograms were reconstructed with eye-safe helium-neon lasers. Collimated illumination of the combustion environment gave reconstructions with 2 micron resolutions; however, for most propellants thermal cells severely refracted the laser light. Diffuse rear-lighted reconstructions gave resolutions of 6 microns due to enhanced speckle effects due to the wavelength difference between the ruby and helium-neon lasers. Viewing the projected holographic images with a moving screen improved resolution by 30%, or to 4 microns. Acquisition of quantitative particle size and spatial distributions was demonstrated by manual measurement of the 3-D position and size of the individual reconstructed particle images from the hologram.

Laser pulse durations shorter than the conventional 50 nanosecond Q-switch pulses are required with metallized propellants to avoid time-averaged interference effects. A laser-triggered spark gap pulse chopper was used to reduce the ruby laser pulse duration to $\sim$ 10 nanoseconds. Even shorter pulses are desired. Pulse widths of 2-5 nanoseconds are achievable with mode locking techniques.

Particle velocities from 1 cm/sec - $\sim$ 1 km/sec can be measured from double exposed holograms in a special holocamera with separate reference beams. Each pulse was routed along a separate reference beam path. The two images can be reconstructed separately, avoiding any confusion about the particle identifications and motions.

Holographic interferograms can be recorded. Conventional (first exposure prior to combustion) double exposure holographic interferograms can be recorded only with collimated interferograms. Rapid double exposure interferograms can be recorded with diffuse illumination with pulses separated by less than 100 microseconds. Interferograms show optical path changes (products of refractive index and physical length of change). The technique can be used to compute gas density.

Reflected light holograms can also be recorded with 50 nanosecond pulses. These showed particles by their scattering of the laser light as well as the burning surface when it was viewed obliquely. Surface detail was poor, probably due to the transparency of the surface to laser light.

The different types of recordings are summarized in Table VII.

In summary, it was found that laser holography can acquire microscopic quantitative data on the combustion characteristics, particle sizes, particle velocities, thermal cells and gas density variations of small burning solid rocket propellants at high pressures. The technique should be applicable to a wide variety of combustion phenomena. Clearly, techniques for handling the vast amounts of information on a hologram need to be developed. Table VII summarizes holographic techniques used to record combustion phenomena.

Table VII

SUMMARY OF HOLOGRAPHIC TECHNIQUES USED TO RECORD COMBUSTION PHENOMENA

Illumination	Collimated Scene Beam	Diffuse Scene Beam	Reflected Scene Beam
Single, 50 nsec Laser Pulse	Plume characteristics. Surface sillhouetted against bright background. Highest resolution. Bothered by refractory effect of hot gases.	Good conditions for particle census. Resolution loss due to speckle. Particle field free of gas refractory effects.	Examination of surface. Qualitative information only.
Single, 10 nsec, best for highly metallized fuels	Same as above. Has better time resolution. Able to freeze the more violent gases. Has lower output energy from laser, thus fogging problems.	Same as above, but danger of fogging due to lower output from laser.	Examination of surface. Qualitative informatior only.
Interferometry	Only means of recording interferograms without washing out fringes. Fringes hide particulate. Can yield burn rates of surface.	Fringes washed out. Not useful technique.	Not applicable.
Differential Interferometry	Shows rate of fringe growth. Can show burn rates between pulses, thus uniformity of burn along surface.	Particle count and direction of movement suspect. Fringe growth rate is obtainable and fringes are free of refractory effects.	Not applicable.
Rapid Double Pulse, Two Reference Beams	Resolution hindered by refractory effects of hot gases.	Best condition for velocity measurement recordings. No fringes to hide particles.	Not applicable.

VII. RECOMMENDATIONS

The biggest improvement would be the use of a doubled YAG laser to record the combustion holograms. As noted earlier, such holograms could be reconstructed without any change in wavelength. Reconstruction would be with, preferably, a continuous wave doubled YAG laser, although a pulsed xenon gas laser could also be used.

Mode locking tests should be completed to generate shorter laser pulses.

The photodiode technique for pulse chopping should be carried to completion (developed).

Amplifier techniques should be developed to increase the energy of the 10 nanosecond-pulsed-chopped light pulses.

Systems have to be developed for the automatic (electronic) retrieval of particle size and position data (spatial coordinates) from the reconstructed images.

ACKNOWLEDGEMENTS

The authors want to acknowledge the support and guidance of Dr. D. George, Technical Contract Manager, for his interest and contributions to the program. We also want to thank Dr. Lee O. Heflinger for his suggestions and guidance, particularly on the development of the lens-assisted technique.

APPENDIX I

ORIGINAL CONTRACT STATEMENT OF WORK*

* The contract started June 21, 1976. It was completed December, 1977.

OFFICE OF ORGIN: AFRPL/DYSC
DATE: 27 May 76

EXHIBIT "A" to Contract Subline Item 0001AA

STATEMENT OF WORK

1.0 INTRODUCTION:

1.1 Laser holographic techniques have been used successfully in characterizing liquid droplet spray fields under rocket hot firing conditions by yielding quantitative data. Initial contractual programs sponsored by the Jet Propulsion Lab (1968) and the AFRPL (1969) demonstrated the feasibility of applying holography to investigate the combustion processes in liquid rocket engines. A subsequent RPL in-house program, Hot Spray Characteristics (1973), applied laser holography to acquire quantitative propellant droplet size and spatial distribution data for development of correlation equations and distribution functions to obtain better modelling of the atomization process in a combustion environment.

1.2 Analogous to the need for droplet data to model liquid rocket combustion is the need for particle size and spatial distribution data to model combustion of metallized solid rocket propellants. Particle size and spatial distribution information is used in the analysis of steady state and oscillatory combustion processes. Acquisition of accurate, quantitative data under actual hot firing conditions will lead to better understanding of solid propellant combustion. This in turn will aid in the development of more accurate analytical models to predict performance and combustion stability.

1.3 Certain diagnostic and particle data acquisition equipment and techniques, such as microphotography in window bomb tests and the particle collection device, are presently being used for solid propellant combustion investigations. These are useful but have some limitations which can be overcome if laser holography can be successfully applied. The holographic technique can provide a 3-dimensional reproduction of the total particle-gas flow field, without disturbing the field, with one pulse of a ruby laser. Holography provides the opportunity to acquire quantitative data of particle size, velocity and burn rate, while microphotography data is qualitative in nature. Also with holography the particles can be observed in their actual location in the gas field, whereas this can not be accomplished with the particle collection device.

1.4 Early attempts in 1969 to apply laser holography to solid propellant combustion investigations met with very limited success due to a number of reasons. The effort was too small in scope to permit adequate development to demonstrate feasibility and a poor choice of experimental apparatus and propellant sample size prevented the recording of high quality holograms. Since that time extensive experience has been acquired in holographic

applications and a number of advances have been made in the development of holographic techniques. These advances, when coupled with the need for accurate particle data and the potential advantages of the holographic technique, as discussed in Paragraph 1.3, provide sufficient grounds for the re-examination of the application of holography to the characterization of solid propellant combustion. Successful application of the holographic technique will enhance better understanding of the burning characteristics of solid propellants and provide an increased capability to better characterize the combustion of new and existing solid propellants.

2.0 OBJECTIVES:

2.1 To demonstrate feasibility and develop the capability to apply the laser holographic technique to quantitatively characterize the particle size and spatial distributions in the combustion gases near the surface of a burning metallized solid rocket propellant.

2.2 Additional objectives are to develop the capability to 1) make detailed observations of the burning propellant surface characteristics, and 2) measure the velocity of the smallest discernible particles and aluminum burn rate by multiple pulsing laser holographic methods.

2.3 The final objective, once the objectives of para 2.1 and 2.2 are met, is to modify the existing AFRPL laser holographic equipment to render it capable of acquiring the types of data specified in para 2.1 and 2.2.

3.0 SCOPE:

This program will be conducted in three phases as described below:

3.1 Phase I: Feasibility Demonstration and Technique Development.

Non-combustion laboratory and bench tests will be conducted to obtain the proper optical component arrangements to achieve the objectives of the program. The scene volume for these tests will be a simulated combustion bomb in which an inert propellant grain, presized particles or resolution target will be installed to determine resolution capabilities and develop the various holographic techniques to acquire the different types of data of interest. Initial combustion tests will also be conducted in this phase to demonstrate feasibility of the techniques in a combustion environment.

3.2 Phase II: Development and Verification of Holographic Techniques

In this phase, the various holographic techniques will be applied to combustion tests in a window bomb for further development, such as proper

setting of the scene-reference beam intensity ratio, in the actual environment of interest. Tests to demonstrate adequate resolution and multiple pulse results under hot firing conditions will be conducted for verification of the techniques.

3.3 Phase III: Installation and Demonstration of the AFRPL Laser Holographic Equipment

Upon successful completion of Phases I and II, the existing AFRPL laser holographic equipment will be modified to render it capable of acquiring the various types of data of interest to establish an in-house capability.

4.0 WORK TO BE ACCOMPLISHED:

4.1 Phase I: Feasibility Demonstration and Techniques Development

4.1.1 The contractor shall survey the various holographic techniques for their applicability to the investigation of burning solid rocket propellant. Data of interest about the propellant includes: 1) metal particle size and spatial distribution near the surface of a burning propellant at pressures up to 1000 psig in a combustion window bomb apparatus, 2) burning surface characteristics, 3) burning rate of metal particles in the gas stream, 4) velocities of at least the smallest discernible particles in the gas stream above the burning propellant surface and 5) flame density gradients. Holographic techniques such as bright field holography, scattered light, lens-assisted, transmission, reflected, off-axis, in-line, interferometry, etc. shall be considered for their applicability to acquiring the different types of data of interest. The contractor shall also assess the adequacy of the presently used window bomb as an experiment apparatus for application of holographic techniques. Any modifications required such as placement and orientation of the windows, shall be made.

4.1.2 The different techniques shall be assessed for their data acquiring capabilities. A tabulation of the advantages and disadvantages of the various techniques as applied to acquiring the data of interest shall be made. Items of consideration shall include resolution capability in a high pressure combustion environment, ease of set-up, depth of field, ease of operation and data acquisition, ease and resolution of holographic reconstruction for data retrieval, cost of system acquisition, operation and data retrieval, etc. The conclusions of this study shall be presented to the Air Force with recommendations on which techniques should be pursued in this phase to demonstrate their feasibility for acquiring the data of interest. The contractor shall also submit a plan for approval by the Air Force detailing how the feasibility demonstrations of the holographic techniques are to be conducted.

4.1.3 A systematic approach shall be taken in conducting the feasibility demonstrations of the various holographic techniques. In this phase, technique development shall be initiated by conducting non-combustion laboratory and bench tests. Experiments shall be conducted to obtain the proper optical component arrangements, laser pulse width, time between pulses, etc. The scene volume for these tests shall be a simulated combustion window bomb in which an inert propellant grain, presized particles or resolution target is installed to determine resolution capabilities. The resolution objective of this program is the capability to resolve particles as small as 3 microns in a combustion environment with a minimum amount of equipment arranged in a simplified manner. Cold flow tests shall be conducted to calibrate particle velocity data acquisition techniques and holographic interferometry. Dimensions and information concerning the existing window bomb will be provided by the Air Force. In addition, the initial combustion tests to demonstrate feasibility of the techniques when applied to a combustion scene shall be conducted. Propellant samples for these tests will be supplied by the Air Force.

4.2 Phase II: Development and Verification of Holographic Techniques.

4.2.1 After demonstrating the techniques in a non-combustion and combustion environment, the contractor shall recommend to the Air Force for approval those techniques to be pursued further for development and verification under hot firing conditions. The combustion tests will be conducted with various propellants being burned in the window bomb at pressures up to 1000 psig. Tests shall be conducted at 500 and 1000 psig. The propellant test samples shall be provided by the Air Force and will include aluminum content from a few particles, of various sizes, to 20% by weight. The window bomb will also be provided by the Air Force. After selection of the techniques to be further developed under hot firing conditions, the contractor shall submit a test plan to the Air Force for approval for development and verification of the techniques.

4.2.2 Tests to demonstrate adequate resolution of particle sizes and the propellant surface characteristics, multiple pulse and flame density gradient results under the various hot firing conditions shall be conducted for verification of the holographic techniques. As part of the verification task, the contractor shall show that the program objectives have been met by reconstruction and evaluation of the holograms and interferograms. The contractor shall also take simultaneous still photographs of the holographic scene to aid in the verification process. In addition, some of the verification test holograms shall be sent to the Air Force for reconstruction and application of the data retrieval and reduction techniques developed under the Liquid Injection into a Supersonic Stream and Hot Spray Characteristics programs. The Air Force shall feed back information to the contractor concerning the data retrieval results.

4.3 Phase III: Installation and Demonstration of the AFRPL Laser Holographic Equipment.

4.3.1 Upon completion of Phase II, the Air Force shall evaluate the results and degree of success achieved in both Phases I and II, and shall assess the desirability of demonstrating the capability of existing laser-holographic equipment at the AFRPL for use in the characterization of solid propellant combustion. RPL has two laser systems which shall be considered for modification to render one of them capable of multiple pulsing, reduced pulse width and improved optical resolution. These systems are:

MANUFACTURER:	Holobeam	TRW
TYPE:	Pulsed Ruby Series 300	Pulsed Ruby
OUTPUT ENERGY:	0.150 Joules	1-3 Joules
PULSE WIDTH:	16n sec	50n sec
POWER SUPPLY:	5KV	5KV
CAPACITOR BANK(S):	220 μf	375 μf (2 each)

The contractor shall evaluate the feasibility and practicability of modifying one of these systems, for subsequent use by RPL, and submit his recommendations to the Air Force. Any modifications, fabrication and/or purchase of new auxiliary equipment are to be accomplished by the contractor upon prior Air Force approval. The contractor shall provide detailed information on the recommended modifications and identify and list all new items along with statements justifying the modifications and equipment acquisition. It is estimated that these modifications and equipment purchases would be approximately twenty percent of the total program.

4.3.2 After the modifications and procurement of new equipment are completed, the contractor shall demonstrate proper functioning of these at the AFRPL with a series of combustion tests similar to the verification tests of Phase II. Satisfaction of contractual requirements will be accomplished upon attaining results equal to or better than the verification test results of Phase II.

4.3.3 The contractor shall provide a detailed instructional manual which includes the operational procedures for the various techniques, equipment maintenance procedures and a list of replacement parts. Contractor personnel shall instruct AFRPL personnel in the application of the techniques and use and routine maintenance of any new equipment.

4.3.4 The contractor shall conduct a preliminary study to insure that laser system operation is conducted in a safe manner. ANSI Z136.1 shall be used as a guideline for this study. The main objectives of the study are to minimize physical harm to personnel and unintentional catastrophic failure of hardware.

APPENDIX II

APPROVED PROCEDURE FOR OPERATING
THE RPL COMBUSTION BOMB AT TRW, SPACE PARK

TRW
SYSTEMS GROUP
ONE SPACE PARK · REDONDO BEACH · CALIFORNIA 90278

INTEROFFICE CORRESPONDENCE

76.4351.3.1-068

TO: TRW Health and Safety CC: DATE: August 10, 1976

R. F. Wuerker

SUBJECT: Holographic Pressure Vessel Test System, R1, Room 1059B

FROM: R. F. Wuerker
BLDG R1 MAIL STA. 1062 EXT. 61816

A high pressure nitrogen gas test system has been assembled for studying the combustion of solid rocket samples in a GFE combustion bomb. The bomb will accommodate fuel samples no larger than 1/4 inch cubed. Standard operating pressures will be either 500 or 1000 lbs/in^2 of nitrogen gas.

Bottled sources (2500 or 6000 psig) of compressed nitrogen gas will be used to pressurize the combustion bomb. The chamber will be vented so that smoke and products of combustion do not accumulate and obscure viewing, yet maintain the desired 500 or 1000 psig operating conditions. Gas flow duration will be of the order of 5-10 seconds. The gas will be vented to the roof.

The complete system is shown schematically in Figure 1.

RD-1 is a rupture disk with a 1977 psig rated failure.

RV-1 is an adjustable relief valve set at 1200 psig.

RV-2 is an adjustable relief valve set at 680 psig.

M-3 is a Bourdon type pressure gauge which has been calibrated against a high quality .1% FS accuracy Heise Gauge. M-3 pressure range is 0 - 1500 psig.

SV_1,SV_2 are high quality stainless steel body, normally closed, solenoid valves. They are rated at 3000 psig at cryogenic temperatures, and have been pressure tested by the manufacturer at 4500 psig. Their estimated burst pressure is 7500 psig.

SV_3 is a similar valve to the above with the exception that it is a three-way valve whose normally open condition can be closed upon activation. Any loss of power in the building will allow the system to vent through this valve.

MV-2 and 4 are emergency hand valves which are normally closed. They provide bypass functions should the solenoid valves fail.

MV-5 is a blocking valve which disables the 68° relief valve whenever the system is operated at 1000 psig. It is opened whenever operation is at 500 psi conditions.

The system is plumbed such that at no time will any N_2 gas be released into the working area. All lines are relieved into a 2" vent line to the roof.

Operating Procedures

A. Remove unessential personnel from room.

B. Verify N_2 bottles valve (MV-1) is closed and that the valve power supply is off.

C. Follow steps:

1. A sample of propellant fuel is to be mounted on the pedestal located inside the pressure vessel.*

2. The gas feed line is then to be connected to the combustion bomb and the electrical wire from the ignitor connected to the power line.

3. A film plate is to be positioned in the holocamera, and the shutter is to be cocked.

4. The lights in the room (1059B) are to be turned off. The dark slide is pulled. The operator leaves the room via the darkroom (1059A) door. The double doors leading to 1059B from 1059 will be locked from the inside of 1059B where the high pressure vessel is located. No personnel are to be in 1059C when the system is pressurized.**

5. When 1059B is secured, the bottle valve MV-1 can be opened to the regulator.

---

* Solid Propellant Preparation

The propellant provided by RPL is in the form of slabs approximately 1/4" x 4" x 4". From these slabs, the test samples are to be cut. A small aluminum miter box has been designed for accurately slicing the sample. (This footnote continued on page 3.)

**See page 4.

(Continuation of Footnote)

* The fuel samples are presently stored in Bldg. 67 powder room.

1. The sample to be used will be removed from the storage area and then taken to another lab area where a 3/4 inch slice may be cut from the parent slab.

2. The parent slab will then be returned to the powder room.

3. The miter box will then be used to cut propellant to sample sizes. Sample sizes will be placed in a small metal container for transportation to RI for testing.
   a) Face shield and leather gloves are to be worn in the initial 4-inch length slicing from the parent slab.
   b) Only safety glasses need to be used when the sample sizes are handled.

4. Small samples may be glued (with Duco Cement) into position atop the pedestal of the bomb platform.

5. Bomb platform can then be secured into the pressure vessel body.

6. Cut propellant samples will be stored in metal bins in Room 1059B.

6. SV-3 (N.O.) valve is activated closed.

7. SV-1 is opened, allowing the vessel to be pressurized to the predetermined value.**

8. Laser power supply is activated to prime the laser energy banks.

9. Power is applied to the igniter wire.

10. Upon ignition, SV-2 is opened. (Ignition will be monitored via a photodiode device displayed on an oscilloscope.)

11. Laser is fired (this includes activation of shutter).

12. When ignition monitor shows that fuel incandescence is terminated, the valve SV-1 will be closed, thus shutting off the supply and opening SV-3. The vessel should bleed down to zero through SV-3. Pressure release is monitored by MV-1.

13. SV-2 will be closed.

14. SV-3 will be opened.

15. When system is secured, 1059B may be entered to retrieve plate for development in 1059A.

16. When film has been secured, lights may be turned on in Room 1059B for visual inspection of component and plumbing.
    a) Check windows for damage or occlusions.
    b) Check for mechanical dislocations or mechanical damage, loosened window bolts, etc.

17. Reload and repeat as necessary.

**Flow parameters for a given fuel sample will be controlled by the downstream needle valve (MV-3).

Conservation of gas to increase the number of runs dictates the upper bound of the flow, whereas visibility determines the lower bound.

A numerical dial will be put on the needle valve such that for a given fuel sample an empirically known position can be used to control the flow at the test pressure desired.

A chart will be made of needle valve positions vs. static pressure setting necessary to produce a flow condition for both the 500 psi and 1000 psi.

Once this is available, the hologram and fuel sample will dictate the needle valve setting, ergo the pressure setting.

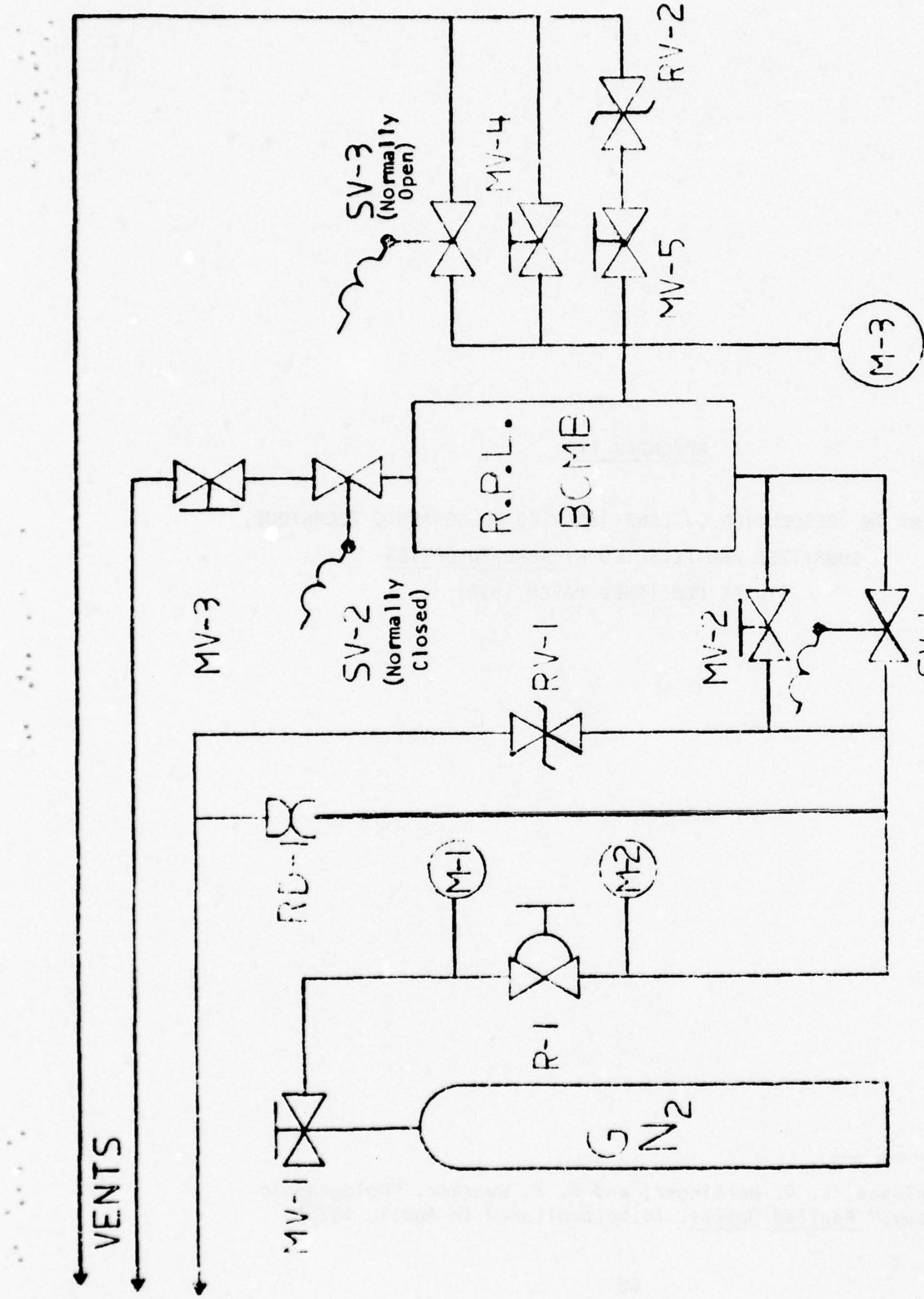

Figure 1. Pressurization System Schematic for R.P.L. Combustion Bomb.

APPENDIX III

PAPER* ON RESOLUTION OF LENS-ASSISTED HOLOGRAPHIC TECHNIQUE,
SUBMITTED AND ACCEPTED BY APPLIED OPTICS
(TO BE PUBLISHED MARCH 1978)

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* R. A. Briones, L. O. Heflinger, and R. F. Wuerker, "Holographic Microscopy," Applied Optics, to be published in April, 1978).

Holographic microscopy

R. A. Briones, L. O. Heflinger, and R. F. Wuerker

An off-axis transmission holographic scheme, in which a 1:1 lens and a hologram are treated as a single rigid entity, is found to reconstruct a 3-D diffraction-limited image when reconstructed, with a reference beam reversed back through the original lens–hologram unit. Reconstruction can be performed with wavelengths other than the recording wavelength, provided achromatic lenses are used, and the reference beam angle is properly changed for reconstruction. Comparisons are made between He–Ne and ruby laser holograms. Two-micron resolution of the combustion of solid rocket propellants at high pressures is achieved at a working distance of 6 cm.

This paper presents the results of resolution tests with the type of lens-assisted-holographic system described in the accompanying paper.[1] The recording apparatus used in the present tests is shown schematically in Fig. 1. It differs from the more conventional holographic arrangements by the rigid attachment of a pair of focusing lenses to a kinematic plate holder. The lenses provide the large numerical aperture needed for resolution. The hologram now records only over a small area the phase and amplitude of the aberrated wave front incident upon it.

Achievement of high resolution with the Fig. 1 arrangement is based upon the fact that aberrations due to the lenses can be *holographically eliminated* (subtracted) by reconstructing the hologram (via the reverse reference beam technique) back through the focusing lenses.[2] For this reason, the focusing lenses are rigidly attached to the kinematic plate holder. The method of reconstruction is diagrammed in Fig. 2. As illustrated, the 3-D recreated images can be examined with a conventional microscope.

For our resolution studies a 1951 optical test pattern was used as the principal test object.[3] The pattern was placed within 2 cm of the hologram's conjugate location. It was rear-illuminated by either collimated or diffuse laser light, the latter being achieved by the insertion of either ground or opal glass diffusers into the scene beam, as shown in Fig. 1. The diffusers give images characterized by speckle or granularity effects. The reference beam was collimated.

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A He–Ne or a Q-switched ruby laser was used to record the holograms in this study. All holograms were recorded on antihalated glass Agfa Gevaert 8E75 plates. The plates were placed in the kinematic plate holder, exposed, removed, and processed, i.e., developed in a 1:4 solution of Kodak HRP, water-rinsed, fixed in a 1:3 solution of Kodak Rapid Fix, water-rinsed again, and air-dried.

For reconstruction, a developed plate is put back into the kinematic plate holder, and the unit as a whole (i.e., lens–plate holder assembly and hologram) was placed before the collimated beam from a He–Ne laser so that the reconstructing beam retraces the original reference beam direction.[1,4] This mode of illumination causes the holograms to generate a backward traveling version of the original wavefront. Phase errors are subtracted away as the aberrated wavefront passes back again through the focusing lenses.[2] In theory, a nonaberrated wavefront emerges from the lenses, identical to the original scene wavefront, but traveling in the opposite direction. A 3-D aerial image is reconstructed beyond the lenses which can be viewed (Fig. 2) with the aid of conventional magnifiers.

Results for the case of collimated (speckle-free) rear illumination are presented in Fig. 3. The first picture in the group is a test of the examining microscope (10×0.3 N.A. objective), namely, a photomicrograph of the finest column of the 1951 chart, rear-illuminated with collimated white light. The second picture is a similar test, except with the chart rear-illuminated with a collimated He–Ne laser beam. It shows the effects of coherent light. The third and fourth pictures are photomicrographs of hologram reconstructions, played back according to the Fig. 2 method from holograms recorded with the arrangement in Fig. 1. The third picture was both recorded and reconstructed with a He–Ne laser (0.6328 μm). The fourth picture was recorded with a ruby laser (0.6943 μm), yet reconstructed with a He–Ne

laser. Comparison between the second and third picture shows that the reconstructed image is on a par with the direct laser image. The fourth picture shows that a 10% change in reconstruction wavelength barely resolves the last row.

Figure 4 is a similar set with the chart rear-illuminated by a ground glass diffuser. As in Fig. 3, the first picture is a direct photomicrograph with white light. The second picture had the white light source replaced by a laser. The third and fourth pictures are hologram reconstructions (as per Figs. 1 and 2), the third being the He–Ne recorded and reconstructed, while the fourth is ruby laser-recorded and He–Ne laser-reconstructed. The ground glass diffuser produces speckle and granularity effects in the laser images. For the fourth pictures, the 10% change in reconstruction wavelength creates noise that drastically degrades the reconstructed image; resolution is at best the sixth row, third column (6-μm bar width). The He–Ne recorded hologram reconstructs to the seventh column-third row (3-μm bar width), which compares favorably with the direct laser photomicrograph (second picture), good to the seventh column-fifth row. White light gives a speckle-free image, good to the microscope's numerical aperture.

To better demonstrate the superior resolution of the lens-assisted technique, a series of nonlens assisted holograms was also recorded. A conventional 75° off-axis two-beam holographic arrangement was used. The chart was 15 cm away from the hologram, a distance that compares with the hologram–object distance in the Fig. 1 lens-assisted arrangement. Sample reconstructions are presented in Fig. 5 for holograms recorded and reconstructed with a He–Ne laser; the first picture is the

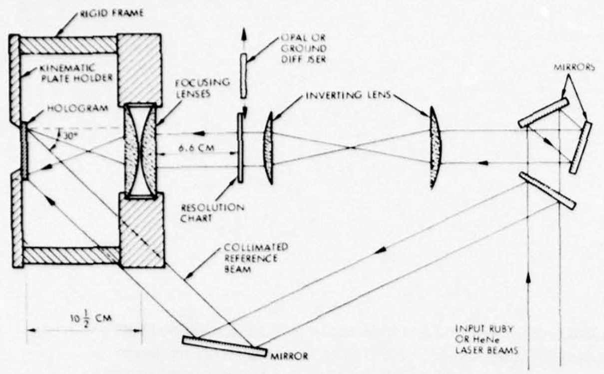

Fig. 1. Schematic of two-beam lens-assisted holographic arrangement.

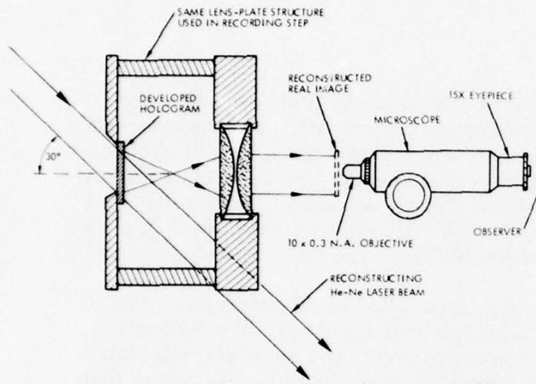

Fig. 2. Method of reconstructing lens-assisted holograms.

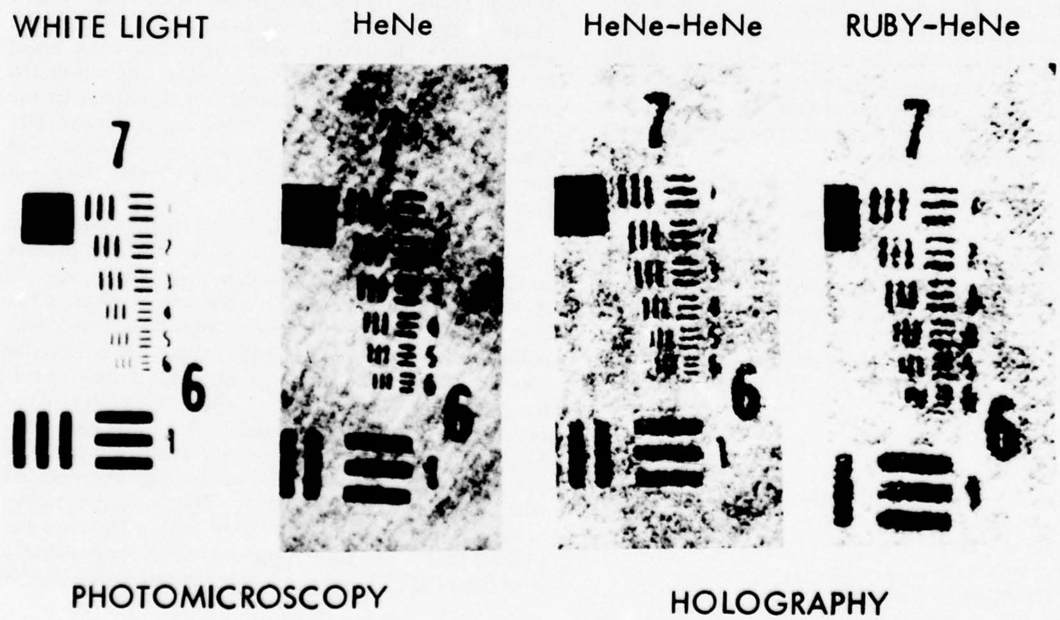

Fig. 3. Comparison between direct photomicrographs and lens-assisted hologram reconstructions. First picture, collimated white light photomicrograph of chart taken with 0.3 N.A. microscope. Second picture, He–Ne photomicrograph. Third picture, photomicrograph of He–Ne laser reconstruction of hologram recorded with He–Ne laser. Fourth picture, same as third except recorded with ruby laser.

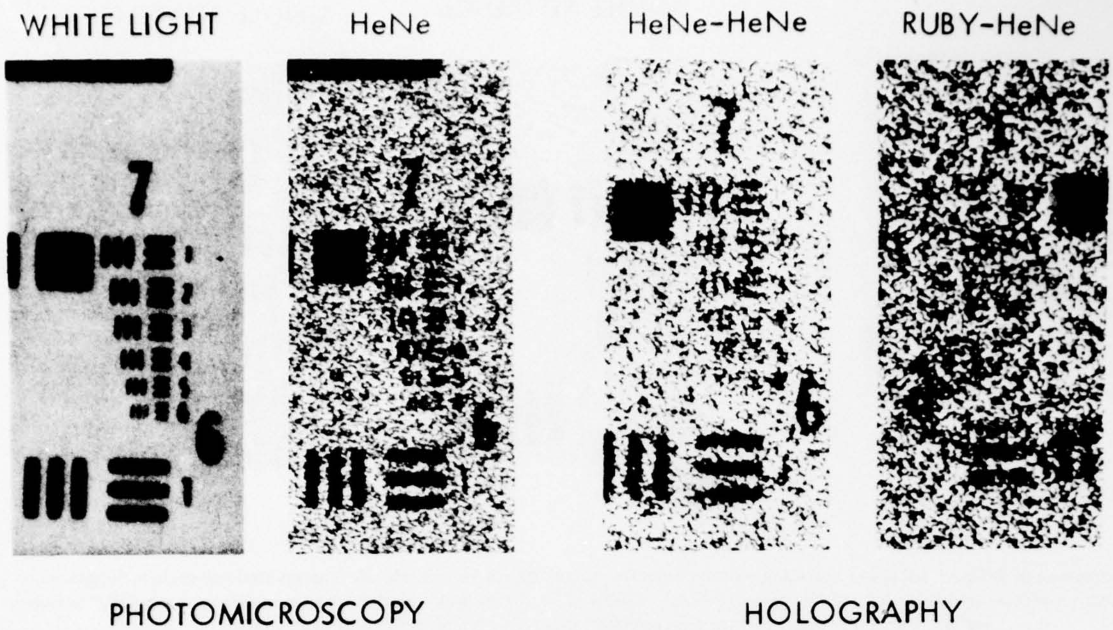

Fig. 4. Comparison between diffuse rear illumination photomicrographs and lens-assisted hologram reconstructions. First picture (left) is direct white light photomicrograph. The second picture is a similar direct He–Ne photomicrograph. The third picture is a photomicrograph (via Fig. 2) of the He–Ne laser reconstruction of a hologram recorded in the Fig. 1 apparatus with a He–Ne laser. The fourth picture is the same as the third except recorded with a ruby laser.

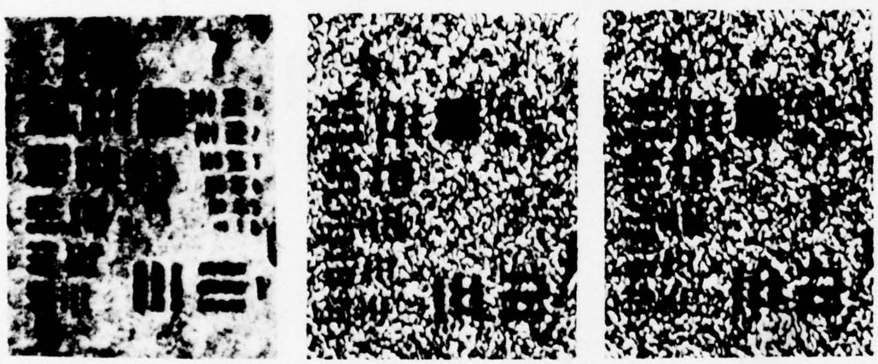

Fig. 5. Photomicrographs of images reconstructed from conventional (nonlens assisted) two-beam (75°) holograms. Left picture, chart rear-illuminated via collimated scene beam. Middle picture, chart illuminated from behind by ground glass diffuser, including the effects of a second reference beam. Third picture, same as second except with only single reference beam.

collimated illumination condition, the second and third pictures are with the ground glass diffuser behind the chart. The middle picture illustrates a reduction in granularity due to the addition (in recording) of a second off-axis reference beam. The third picture is the more conventional single reference beam case. Comparison of these pictures with the reconstructions in Figs. 3 and 4 shows that the lens-assisted technique gives improved resolution (better than a factor of 2).

The double reference beam scheme was also tested for the lens-assisted situation. Sample results are presented in Fig. 6 for the case where the resolution chart was rear-illuminated by an opal glass diffuser. The first picture in this series is the direct (0.3 N.A.) photomicrograph of the opal glass He–Ne laser illuminated chart. The second picture is the reconstruction of the double reference beam He–Ne–He–Ne hologram reconstruction. For this case, the second reference beam was brought around the other side of the Fig. 1 lens–plate structure. (A 60° angle existed between the two reference beams.) The hologram was reconstructed with only one reference beam (i.e., the original, using the Fig. 1 setup). The third picture in this set is the more conventional (also using Fig. 1) single reference beam case, which, except for the opal glass diffuser, is identical to the third example in Fig. 4. Comparison shows that the opal glass produces even finer granularity effects than the ground glass diffuser used in the Fig. 3 tests. The second and third pictures in the present set (Fig. 6) show that the second reference beam yields questionable improvement, hardly enough to justify its use.

Achromatic lenses were also proposed as a way of making the Fig. 1 scheme less sensitive to changes in reconstruction wavelength. Tests with the Fig. 1 arrangement with achromatic lenses instead of simple

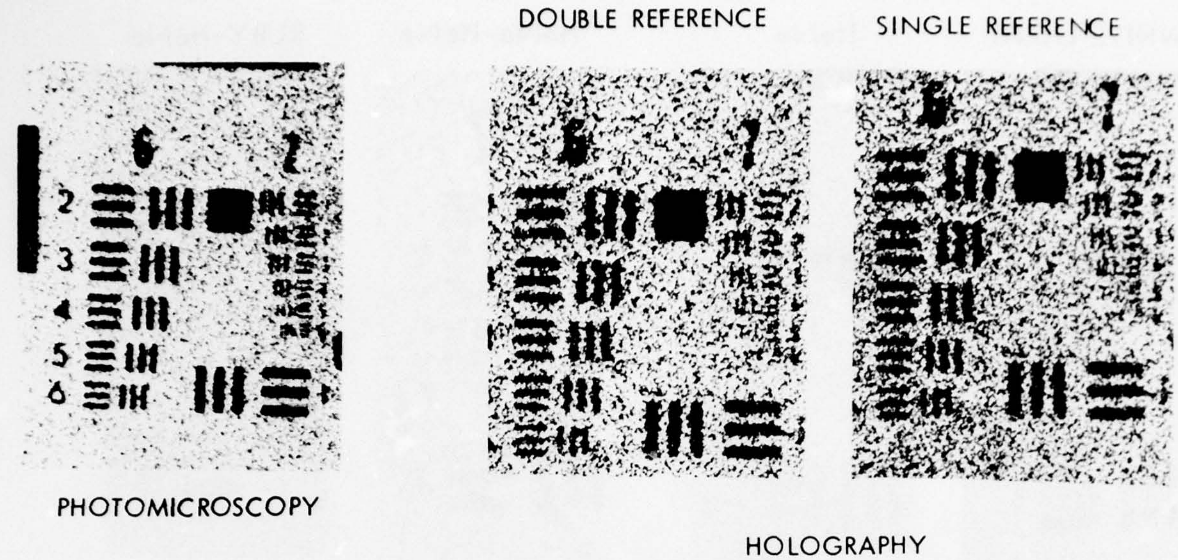

Fig. 6. Comparison of diffuse (opal glass) rear illumination photomicrograph against He–Ne–He–Ne lens-assisted hologram reconstructions. The first picture (left) is the direct photomicrograph (0.3 N.A.). The middle picture was recorded with two reference beams (60° between each). The third (right) picture was recorded (as per Fig. 1) with a single reference beam.

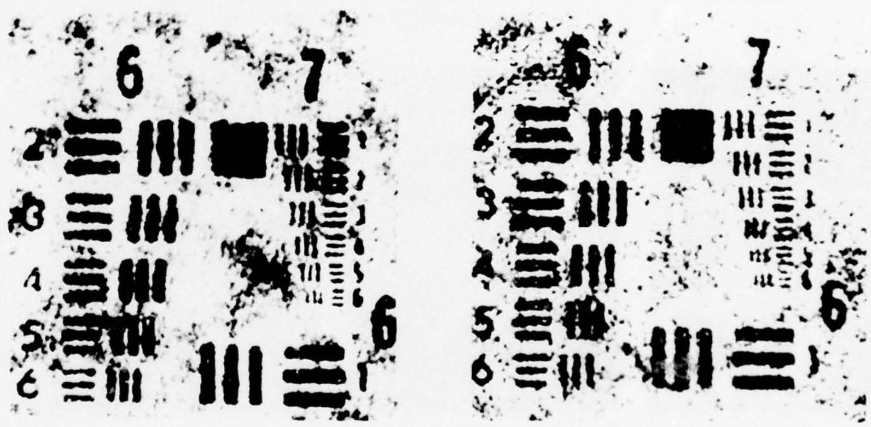

Fig. 7. Comparison of collimated rear-illuminated lens-assisted holograms recorded with achromatic lenses. The left picture was recorded with a He–Ne laser, the right with a ruby laser. Both were reconstructed with a He–Ne laser by the Fig. 2 method.

lenses showed that only the collimated subject light holograms were improved. The diffuse light holograms were no better. Figure 7 shows the collimated illumination examples. Comparison of the second picture with the similar case for simple lenses (i.e., fourth picture in Fig. 3) shows that the achromatic holograms are better.

The tests demonstrated that the lens-assisted technique leads to holograms that reconstruct to the limits set by the system numerical aperture. The best resolution is achieved by recording and reconstructing these holograms at the same wavelength. The collimated mode of illumination is least sensitive to changes in wavelength between the recording and reconstructing step. For diffuse rear illumination, the lens-assisted system gives little, if any, improvement over nonlens assisted two-beam arrangements when there is ~10% wavelength change.

The present study was motivated by particles in flames. Of interest was the smallest size spherical particle which could be resolved by the lens-assisted scheme. This was investigated by recording holograms of the resolution chart dusted with spherical iron carbonyl powder, ranging in size from 3 μm and less. Most of the particles were ~1-μm diam. Results from such a hologram are shown in Fig. 8 which contains collimated (He–Ne–He–Ne) hologram reconstructions at two different focal settings of the examining microscope. In the left picture, the microscope was focused on the chart; particles (on the other side of the glass support)

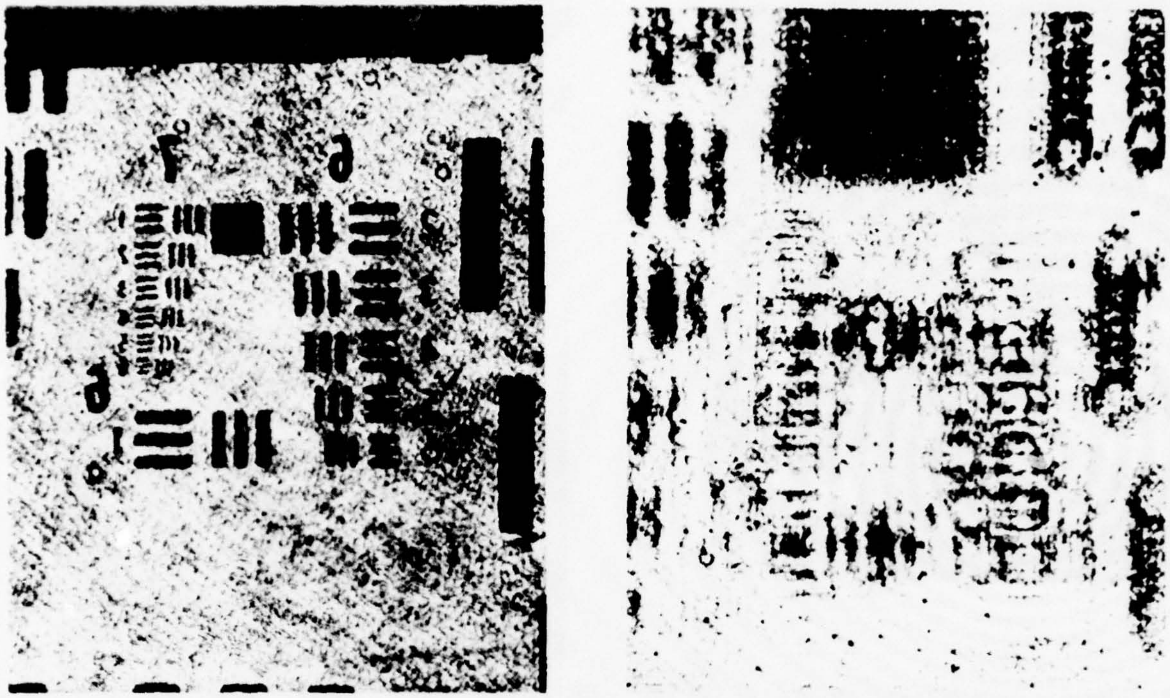

Fig. 8. Photomicrographs taken of the reconstruction of a lens-assisted hologram (He–Ne recorded and He–Ne reconstructed). For the left picture, the examining microscope was focused on the reconstruction of the chart. For the right picture, the microscope was focused on the reconstruction of iron carbonyl particles dusted on the near surface of the 1-mm thick glass plate that supported the chart.

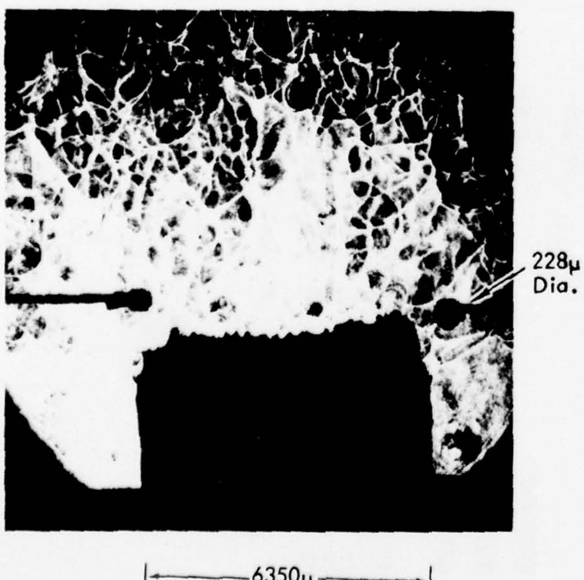

Fig. 9. Low magnification photograph of reconstruction of a (ruby–He–Ne) lens-assisted hologram of the combustion at 25-kTorr pressure of a 6 × 3 × 1-mm sample (initially) of solid rocket propellant (Type MS-23).

are completely out of focus. In the right picture, the microscope was focused on the particles, and the chart is out of focus. Particles smaller than the seventh row–sixth column bar width can be found, demonstrating an ability to discern opaque spherical particles of ~1-μm diam.[5] Figure 8 illustrates the three-dimensionality of the reconstructed images.

The lens-assisted scheme has also been used successfully to record particles in a combustion environment. Such recordings are spectacular in scope and depth of focus and will be described in detail in a forthcoming paper. A preliminary example, however, is presented in this paper to demonstrate not only the practical application of the technique, but also the volume of space (several cubic centimeters) that can be recorded by the Fig. 1 apparatus.[6] Figure 9 is a low magnification photograph of the reconstruction of a collimated lens-assisted hologram of combustion (inside a windowed pressurized combustion bomb) of a 6 × 3 × 1-mm piece of solid rocket propellant. The hologram was recorded with the 80-nse pulse from a Q-switched ruby laser. The silhouette of the fuel sample, the remains of the 228-μm diam ignitor wire, and the convection cells which refracted the incident ruby laser light are seen. A more magnified portion of the reconstruction is presented in Fig. 10. Small particles can be seen. An even more magnified portion (20×, 0.5

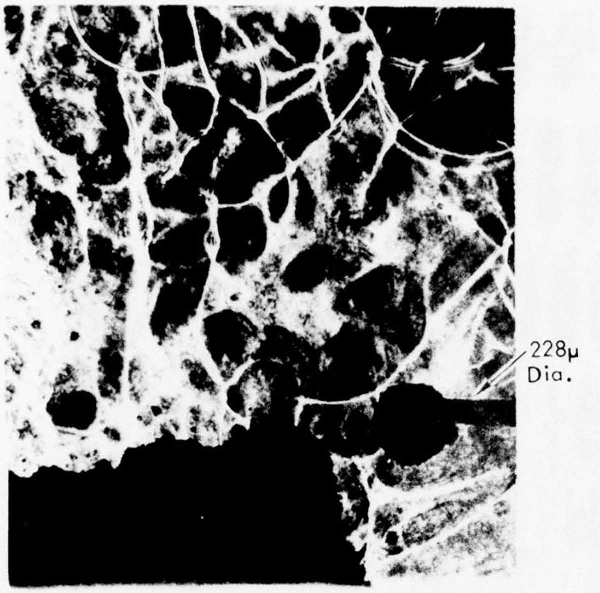

Fig. 10. Enlarged portion of the reconstructed image shown in Fig. 9 (taken with 10×, 0.3 N.A. objective).

Fig. 11. Further enlargement of portion of same image reconstructed from hologram and shown in Figs. 8 and 9. This picture was taken with 20×, 0.5 N.A. objective.

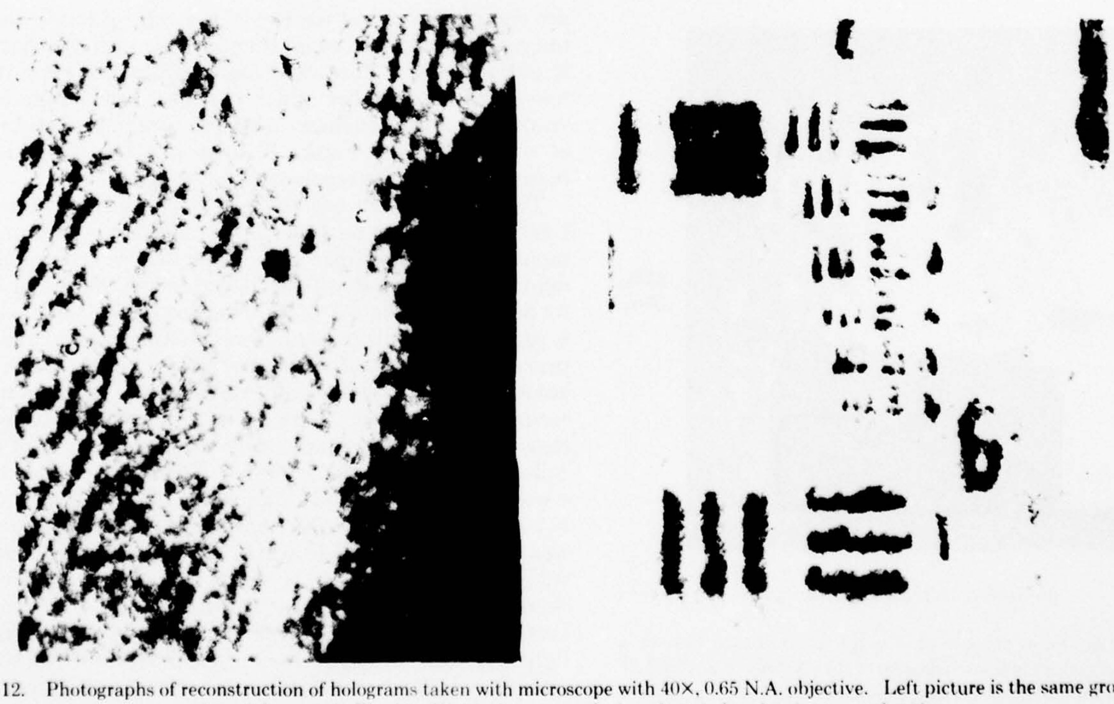

Fig. 12. Photographs of reconstruction of holograms taken with microscope with 40×, 0.65 N.A. objective. Left picture is the same grouping of particles seen in Fig. 10. Right picture, resolution chart in bomb prior to combustion.

N.A. objective) is presented in Fig. 11. For this picture, the examining microscope was focused on a group of particles near the burned tip of the ignitor wire. Size can be judged by the 7-μm spaced interference fringes (due to the refraction of laser light by thermal cells). The particles in this group were even further magnified (40×, 0.65 N.A. objective). Such a picture is presented in Fig. 12. It represents the maximum magnification that the present lens-assisted holograms can be enlarged. Particles of ~2–3-μm size are seen. A photograph of the reconstruction of the resolution chart, made just prior to the actual firing, is included. The resolution chart was placed in the combustion bomb and recorded through the 19-mm thick quartz viewing port, the 13-mm thick interference filter, and 70 and 96 (1.0 N.D.) Wratten filters (all included to suppress flame light).[7] The resolution chart picture shows that a ruby hologram still yields high resolution when recorded through this amount of glass.

Changes in focus enabled us to view and record particles throughout the entire combustion environment. Figures 8–11 show the high resolution capability of the lens-assisted holographic scheme in the practical study of combustion.

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1. L. O. Heflinger *et al.*, Appl. Opt. **17**, 951 (1978).
2. H. Kogelnik, Bell Syst. Tech. J. **44**, 2451 (1965).
3. The 1951 resolution chart consists of both vertical and horizontal three-bar arrays whose spatial frequency (SF) varies according to the equation

$$SF = 2\left\{\text{column \#} + \frac{\text{row \#} - 1}{6}\right\} (\text{lp/mm}).$$

The smallest divisions correspond to the seventh column and six row, a spatial frequency of 228 lp/mm (spatial period of 4.4 μm or individual bar widths of 2.2 μm).
4. Reconstruction of the 1951 chart holograms to highest resolutions could be achieved without recourse to the special alignment technique described in Ref. 2. For example, holograms recorded with a ruby laser and reconstructed with a He–Ne laser required a 9½° decrease in reference beam angle to compensate for the wavelength difference. The optimum reference beam angle was found by carefully tuning the beam relative to the hologram while microscopically observing the reconstructed image.
5. A similar test was conducted with transparent 2.4 μm polystyrene spheres. The spheres were harder to reconstruct due to their lower contrast. They could just be seen in the reconstruction.
6. Larger focusing lenses would permit recording even larger volumes at similar resolutions.
7. These holograms were reconstructed back through a window section and a piece of glass that simulated the interference filter.

APPENDIX IV

COMPANION PAPER* SUBMITTED SIMULTANEOUSLY TO APPLIED OPTICS WITH PAPER IN APPENDIX III. THIS PAPER DESCRIBES THE INITIAL USE OF THE LENS-ASSISTED TECHNIQUE IN THE STUDY OF MARINE PLANKTON. NO RESOLUTION MEASUREMENTS WERE MADE.

* L. O. Heflinger, G. L. Stewart, and R. C. Booth, "Holographic Motion Pictures of Microscopic Plankton," Applied Optics (to be published in April, 1978).

Holographic motion pictures of microscopic plankton

L. O. Heflinger, G. L. Stewart, and C. R. Booth

A high-speed cine-camera system utilizing holographic principles to circumvent the restrictive depth of field limitations of photomicrography is being used for behavioral studies of rapidly moving marine zooplankton. High resolution is achieved from small format, flexible 35-mm movie film by the development of a lens-assisted holocamera. The lens images subjects close to the film in the recording process in order to reduce flatness requirements of the film. Aberrations introduced by the lens are cancelled by positioning it in precisely the same relationship to the film during reconstruction as it occupied in recording. New alignment and pathlength matching techniques for complex holocameras were developed.

I. Introduction

The ability of holography to circumvent the restrictive depth of field limitations of photomicrography is especially significant when motion pictures are desired of rapidly moving microscopic objects. Of particular interest to us is the study of the behavior of free-swimming planktonic marine organisms. By allowing an animal to swim relatively unrestricted in an aquarium, while being recorded, it is thought that close to natural behavior may occur. In observing certain behavioral sequences, high frame rates are necessary to reduce loss of information on activities occurring between frames. A cine-holographic configuration for recording free-swimming plankton movements was developed by Knox and Brooks.[1] It was also the basic system used in the cine-holocamera described by Stewart *et al.*[2] However, this on-axis system lacked the high resolution required to study important details of plankton behavior such as food manipulation during feeding and other small appendage movements. The system has now been converted to an off-axis mode of hologram production, and further refinements were made to achieve improved resolution (Fig. 1).

This paper describes the configuration which achieves improved resolution at a long working distance (10 cm) with a standard 35-mm movie film format (18 × 24 mm) e.g. Kodak SO-424 or AGFA 10E56.

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II. Lens-Assisted Holocamera

The flexibility of 35-mm film makes it impossible to guarantee that the film shape during reconstruction is identical (to wavelength accuracy) to its shape during holographic recording. To help overcome film differences between recording and reconstruction, a relay lens system was developed which has the purpose of forming images of the subjects in the vicinity of the holographic film. The lens operates at 1 to 1 with an input numerical aperture of 0.24 (5-cm diam, 10-cm working distance). Information from a given subject is confined to a limited portion of the 35-mm film. For example, if the image is 1 cm or closer to the film, the hologram need be faithful only over a circle of 5-mm diam or less. Thus, all that is required is that the movie film be flat over the same limited area in both recording and playback. In comparison, a nonlens-assisted holographic system with an input numerical aperture of 0.24 and a 10-cm working distance between subject and film plane would require the film to be faithful to wavelength accuracy over a 5-cm diam circle.

It is neither intended nor desirable to form a sharp image at the film plane as saturation effects would limit the faithfulness of the reconstruction. Hence, a lens in which the aberrations are not fully corrected is used. The lens system we adopted after preliminary trials consists of two planoconvex lenses with the curved sides toward each other.

High resolution is achieved in reconstruction by playing the image back through the same lens used in recording. Thus, all the aberrations introduced by the lens during recording are canceled.[3] To achieve this cancelation, it is necessary to reverse the direction of the reference beam in reconstruction so that the subject light passes through the lens in the opposite direction, subtracting the aberrations (Fig. 2). This reversal must be precise, and thus it is critical that the positioning of

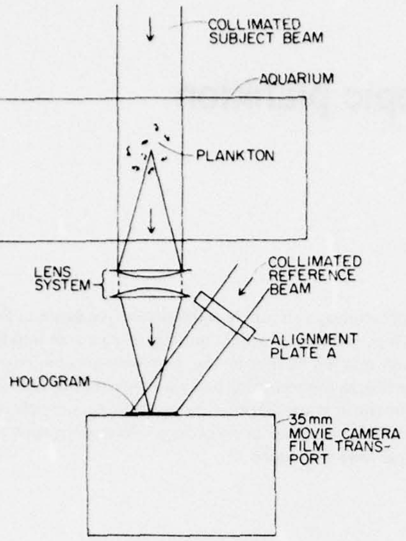

Fig. 1. Recording system.

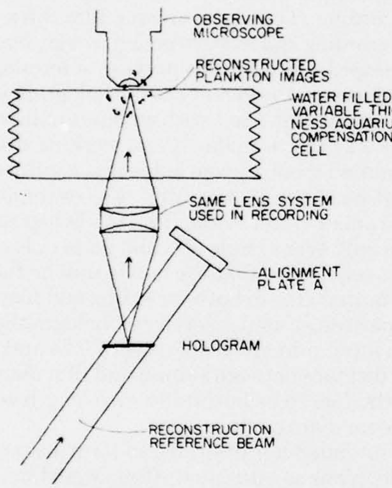

Fig. 2. Reconstruction system.

the relay lens in relation to the hologram must be the same during reconstruction as during recording. In our system, the water cell shown in Fig. 2 is used to compensate for the water and walls of the aquarium which was holding the plankton during recording.

It was not possible to use the recording movie camera transport for reconstruction because certain mechanical components would have obstructed the reversed reference beam. Thus, it was necessary to construct a custom reconstruction film transport. The recording position between lens and hologram was mechanically duplicated in the reconstruction assembly by a series of micrometer measurements. The lens is mounted in such a way that once aligned it may be shifted back and forth between recorder and reconstructor without repeating the measurement process.

Precise reversal of the reference beam during reconstruction is achieved as follows: In the recording arrangement shown in Fig. 1 there is an alignment plate. This is a plane parallel plate of glass which is placed in a kinematic holder rigidly attached to the lens assembly. Prior to recording, the collimated reference beam is adjusted to be perpendicularly incident on this plate. The plate is then removed, and the holographic recordings are made. During alignment for playback, the same plate is placed in its kinematic holder attached to the lens assembly, and the collimated reconstruction reference beam is adjusted to be perpendicularly incident on the plate but from the opposite side used during recording alignment (Fig. 2). The alignment plate is removed during actual reconstruction. The reconstruction reference beam is thereby precisely reversed relative to recording by this process.

The attainment of perpendicular incidence on the alignment plate in either recording or playback is achieved by the arrangement shown in Fig. 3. Here a plane parallel splitter glass (B) diverts a portion of the reference beam to a corner reflector (C) which returns the light through the splitter to lens (D) forming a point image at (E). The other portion of the reference light passes through splitter (B) to the alignment plate (A) which returns a portion to be reflected by splitter (B) to lens (D) and forms a point image at (E'). Adjustment of the reference beam direction to cause (E) and (E') to coalesce guarantees perpendicular incidence of the reference beam on the alignment plate (A). The plate (A) and splitter glass (B) are then removed before recording or reconstruction.

When the same wavelength is used for both recording and reconstruction, the above system directly achieves the desired precise beam reversal. The system has been used in this manner with a pulsed (40-μsec) argon laser for recording with playback by the same wavelength

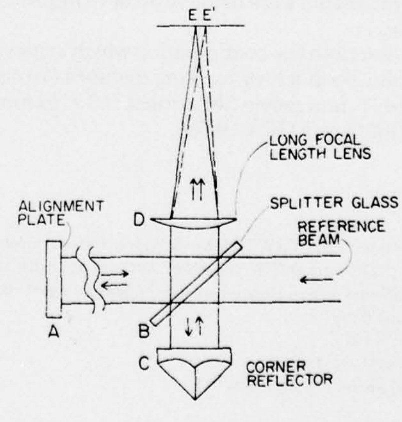

Fig. 3. Reference beam alignment system.

(514.5 nm) from a cw argon laser. In order to achieve a shorter pulse (4 μsec) for higher speed motion pictures, a xenon pulsed laser was also used (535.3 nm). The playback was still done with a cw argon laser (514.5 nm). It was experimentally found that to achieve best resolution under this condition, the playback reference beam angle must be offset from the recording angle by an amount approximately given by the fractional wavelength shift (0.04). Once found, this shift can be reestablished by markers for the appropriate separation of the points (E) and (E') of Fig. 3 during playback alignment. The ability of the system to function under conditions of wavelength shift is described more fully in the accompanying paper (Briones *et al.*).[4]

The pathlengths from laser to hologram should be the same for both subject and reference beams during recording. The tolerance on this is determined by the coherence length of the laser which may be only a few centimeters for pulsed ion lasers. Pathlength matching in our system is complicated because the holocamera is on an X-Y traverse for tracking plankton while the laser is stationary. A direct way of verifying the pathlength match has been found which is useful in complex holocameras. A small ball bearing of 1 mm or 2 mm in diameter is placed at the location of the hologram. At a distance of approximately 20 cm from the ball, a lens (about 25-mm focal length) is held to visually examine the aerial Young's fringe pattern formed from the two point reflections in the ball. As one of the pathlengths is adjusted, the fringes will come and go, the optimum fringe contrast indicating the best pathlength match.

III. Recording Film Transport

The film transport mechanism used for recording is an André Debrie, Appareil GV model G. It is a good quality 35-mm movie film transport, capable of operation up to 200 frames/sec. It is essential that the film be stationary during the exposure interval. In particular, film motion perpendicular to the plane of the film must be sufficiently small so that the difference between scene and reference paths does not change by more than ¼ wavelength during exposure. For our reference beam angle of 35°, this motion must be less than 1.4 wavelengths or 0.7 μm. With the 40-μsec pulse duration of the argon laser, this requirement was not met above 50 frames/sec; however, with the 4-μsec xenon laser, the transport achieves this requirement. In the film plane, motions must be less than the resolution. This last requirement is easily satisfied because it is similar to the requirement for photography where exposure times are much longer.

IV. Reconstruction

A Geneva intermittent motion assembly with special oversize sprocket teeth which reduces lateral film movement has been selected to perform the task of film frame indexing in the reconstruction system. The earlier use of a glass platen and polished metal pressure plate to hold the film flat proved to be unsuccessful because dust particles and irregularities on the film and

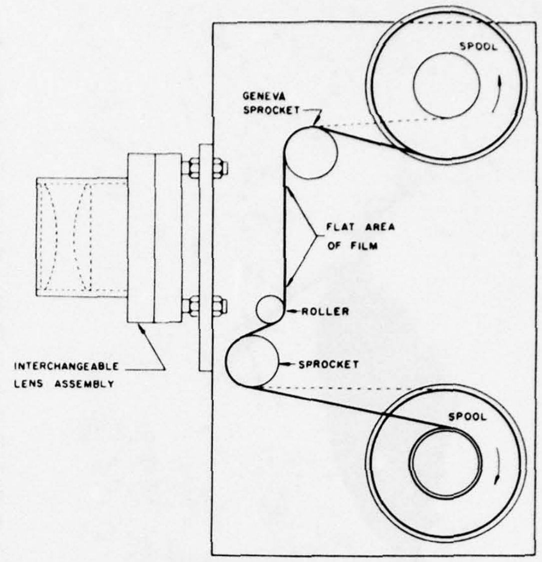

Fig. 4. Reconstruction film transport.

platen produced fine scratches on the acetate base of the film. In most holographic systems, film scratches are not a serious problem, but in our case the relay lens nearly imaged the scratches, introducing a considerable amount of noise in the scene. By incorporating a reverse bend in the film path (Fig. 4) and using two dc electric motors to tension the film in opposing directions, the holograms can be held sufficiently flat to produce high resolution images with no part of the system touching the recording surfaces. The Geneva assembly can be stepped in either direction by hand and with a motor can be actuated at rates up to 24 frames/sec. This allows the operator to move through 30-m (100-ft) rolls of film with reasonable speed when, for example, seeking specific frames. A frame counter and the required logic to find predetermined frames may be added at a later date.

The reconstructed image (Fig. 2), now at the original location of the scene relative to the relay lens, is viewed with standard microscope optics at appropriate magnifications for the specific subject. Scanning the 3-D scene is accomplished by mounting the microscope on an X,Y,Z movement stage.

V. Resolution Considerations

Figure 5 is a photomicrograph of a reconstructed image of a planktonic copepod crustacean. The animal is approximately 5 mm in length and appears almost transparent in seawater. A potential food organism for this species can be seen at higher magnification in Fig. 6. The food, *Ditylum brightwellii*, is a marine diatom (single-celled plant) having a cylindrical or prism-shaped siliceous frustule 30 μm in diam, 80 μm long, with a 2–3-μm diam spine on each end. Both organisms were recorded at a rate of 50 frames/sec.

Fig. 5. Reconstructed image of a marine copepod crustacean.

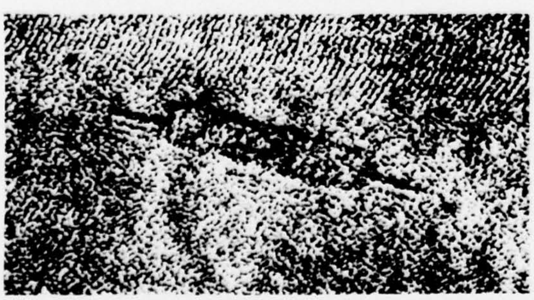

Fig. 6. Reconstructed image of a marine diatom, *Ditylum brightwellii*.

The reconstructed holograms shown in Figs. 5 and 6 were recorded with the illumination arrangement of Fig. 1. It is possible to achieve dark field illumination with the same configuration by simply adding a small diameter stop at the focus of the collimated subject beam during recording. This focus is approximately half-way between the lens and the film. A 2-mm stop will intercept the direct subject light but allows the scattered light to pass on to the emulsion, producing a dark field view upon reconstruction.

Numerical measurements of the resolution have not been made. However, the reconstructed images of holographically recorded plankton were compared side by side with direct visual observations of plankton through the same microscope illuminated with collimated laser light. The resolution of the holograms appeared identical to the direct view, although they do exhibit some excess noise which appears as mottled interference effects and can sometimes mask information. Careful attention to optical surface cleanliness, avoidance of reflections by proper antireflection coatings on the lenses, and avoidance of all unintended scattered light are essential. When these sources of noise light are removed, the holographic images are almost identical to the direct view.

The present system provides microscopic resolution throughout a volume of many cubic centimeters at a working distance of 10 cm. A more quantitative resolution comparison of laser light holographic microscopy to white light microscopy is given in the accompanying companion paper.[4]

This research was supported through National Science Foundation grants OES 75-05385 and OCE 76-21655. The invaluable assistance of Chuck Wood of TRW in maintaining high output from our lasers is greatly appreciated. We also thank J. R. Beers of the Institute of Marine Resources for encouragement and helpful criticism of the manuscript.

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APPENDIX V

SUMMARY OF THE PHASE I AND PHASE II EFFORTS. AN EARLIER VERSION OF THIS PAPER WAS PRESENTED AT THE AIAA 13th JOINT PROPULSION MEETING, JULY 11-13, 1977, ORLANDO, FLORIDA, BY THE AIR FORCE TECHNICAL MANAGER, DAWEEL GEORGE. THE PAPER AS SHOWN HERE WAS PRESENTED BY R. A. BRIONES AT THE JANNAF COMBUSTION MEETING, U. S. AIR FORCE ACADEMY, COLORADO SPRINGS, COLORADO, AUGUST 18, 1977. IT WAS ALSO GIVEN AT THE SPIE CONFERENCE AT LA JOLLA, CALIFORNIA, AUGUST 26, 1977. FINALLY, IT WAS ACCEPTED FOR PUBLICATION AT THE AIAA IN THEIR SERIES ON THE *APPLICATION* OF LASERS TO THE STUDY OF COMBUSTION.

HOLOGRAPHY OF SOLID PROPELLANT COMBUSTION*

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Abstract

A two-beam holographic scheme consisting of a 1:1 relay lens and an integral hologram has been used with a Q-switched ruby laser to record high resolution 3-D images and interferograms of the combustion of small (1.5 x 3 x 6 millimeter; .06 x .12 x .25 inch) rocket propellant samples in a high pressure chamber. The holograms were helium-neon laser reconstructed. Images good to 2 micron resolutions were achieved with collimated illumination. Diffuse illumination holograms gave ∿ 4 micron resolutions when viewed on a moving translucent screen. The reconstructed real images yielded particle size distributions. Double exposure holograms yielded either conventional holographic interferograms (first exposure prior to combustion), differential interferograms (both exposures during combustion), or sequential image holograms of the particles. The latter were improved by constructing a holocamera with two separate reference beams. One reference beam was used for one exposure. The other is used only for the second exposure. Such a hologram reconstructs separate 3-D images. From such a hologram, particle motions can be followed and velocities computed without confusion. Metallized propellant holograms showed time-averaged fringe effects when recorded with conventional 50 nanosecond duration laser pulses. The dark fringes in the reconstructions were due to rapid gas expansion. Reducing the laser pulse duration to 10 nanoseconds (by pulse chopping techniques) gave relatively transparent reconstructions. Reflected light holograms (non-lens-assisted) of both the burning surface and the particle clouds were also recorded.

I. Introduction

One of the features of laser holography is its ability to record 3-D images of microscopic phenomena. A single hologram freezes time and records all particles that are in the illumination volume. The holographic image is later reconstructed and examined with a conventional microscope of narrow (several microns) depth of field.

Because holography is based on the coherent properties of laser light, it can record images in the presence of highly incoherent light (such as solid propellant combustion).

Holography can also record superimposed sequential images. Such recordings show the particle field-volume at two different times. For microsecond intervals, small particle displacements give particle velocities. For longer intervals, particle relationships are lost; however, one gains interferometric fringe growth information. Double exposure interferometry is a property of holography which visualizes gas density effects on either a short- or long-term basis.[1]

Holographic techniques have already been successfully applied to a wide variety of particle phenomena, for example: fog particles,[2] cloud ice particles,[3] particles in high speed air flows,[4] liquid propellant combustion,[5] flyash,[6] petrochemical events, plankton,[7,8] etc. The extension of holographic techniques to the recording of high resolution double images of the combustion of solid rocket propellants is the subject of this paper. This paper also includes the descriptions of holocameras constructed for high resolution work, one of which has two independent reference beams, permitting the independent reconstruction of double images.

II. The High Resolution Holographic Apparatus

Successful application of holography to recording the combustion of solid rocket propellants required development of a "holocamera" that gave higher resolutions than earlier schemes.[2,3,4,5] The apparatus is shown in Fig. 1. This type of "lens-assisted off-axis reference-beam holocamera" apparatus was first used to record living plankton.[7,8] It differs from more conventional two-beam arrangements by the incorporation of a pair of relay lenses, between the hologram and the subject being recorded. The lenses are mounted rigidly to the plate holder, and the two are considered to be a single optical element of the holocamera.

Otherwise, the arrangement is "conventional;" collimated light from the illuminating laser is incident upon a beam splitter which divides it into scene and reference beam components. The reference beam is reflected off a mirror and is incident upon the photosensitive hologram plate.** The photosensitive plate records the interference between the two coherent beams of light, namely, the light transmitted through the scene and the collimated reference beam. The beam which passes through the beam splitter is the "holographic scene beam." In the present apparatus, this beam is turned by a pair of mirrors and then passes through a pair of inverting lenses. After the inverting lenses, the scene beam passes through the scene or subject.

* This research sponsored by USAF/RPL under Contract F04611-76-C-0053.

** Usually Agfa 8E75 antihalated plate.

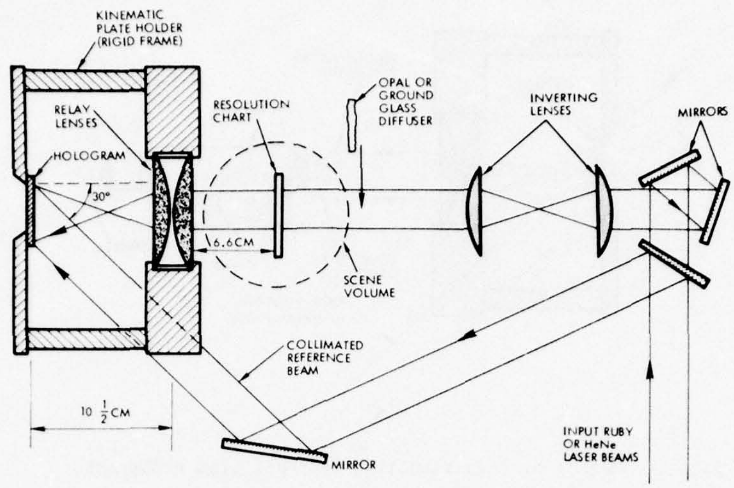

Fig. 1. Schematic of the basic two-beam lens-assisted holographic arrangement used to record solid propellant combustion.

In passing through the subject volume, the light modified by the scene is directed onto the hologram by a set of relay lenses.

The Fig. 1 holographic arrangement is essentially spatially and temporally matched. The mirrors are located so that the two optical paths are identical. Such additional care permits recording holograms with ruby lasers of low temporal coherence. Because of the inversion of the beam by the relay lenses, a pre-inversion is provided by the inverting lens set, all of which insures that the scene beam later combines with the reference beam in the correct right-left, upside-down sense at the hologram (i.e., the two beams are spatially matched). These arrangements compensate for poor spatial coherence of ruby lasers.

The collimated mode of illumination of the scene can be changed by the insertion of a piece of ground glass into the illuminating beam. As shown in Fig. 1, the ground glass is placed behind the subject. The ground glass scatters the laser light over wide angles, giving images that are more three-dimensional in that they exhibit parallax effects. Later it will be seen that ground glass or diffuse illumination eliminates or averages out sharp refractive effects. Diffuse light images of propellant combustion suffer, however, from laser speckle effects, which degrade the resolution by a factor of two over the collimated case, when the hologram is reconstructed with a laser of the same wavelength.(9) For ruby helium-neon holograms, resolution is ~ 6 microns.(6)*

The photosensitive glass plate records the optical interference between the coherent reference and scene beams. After exposure, the plate was removed and developed: typically 30-45 seconds in a 1:4 solution of Kodak HRP developer, water rinse, three minutes in a 1:3 solution of Kodak Rapid Fix, second water rinse (1/2 hour), and air dried.

Next, the integral relay lens-hologram plate structure was set up as shown in Fig. 2. A collimated beam from a 60-milliwatt helium-neon laser was directed back through the hologram along the original reference beam path direction.** In this method of reconstruction, the hologram generates a backward version of the original wave front. Phase errors (due to the relay lenses and any windows or other optics in the original scene path) are subtracted away as the reconstructed wave front passes back through the optical train. Theoretically, a non-aberrated wave front emerges from the lenses, identical to the original scene wave front, but travelling in the opposite direction.

A three-dimensional pseudoscopic aerial image (1:1 magnification) was formed by the recreated wave front. This image could be viewed, as shown in Fig. 2, with a conventional optical microscope. Particle size was measured by equipping the microscope with a travelling cross hair. Particle locations were recorded by mounting the microscope on an x-y-z positioner and measuring its relative positions with dial indicators, or other position sensors (see Fig. 11).

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* Viewing the image through a rotating or moving translucent screen suppresses speckle noise, with the result that resolution improves (~ 4 micron). The technique is shown later in Fig. 11.

** For holograms recorded with a ruby laser, the reconstructing beam passes back through the hologram at a proportionally reduced angle,(9) to properly compensate for the 10% difference between the ruby laser and helium-neon laser wavelengths.(9)

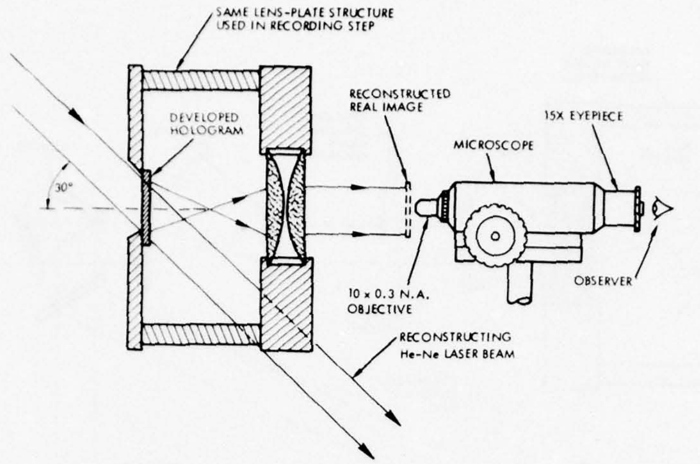

Fig. 2. Method of reconstructing lens-assisted holograms.

Examples of both the three-dimensionality and resolution capabilities of the new lens-assisted holographic technique are shown in Figs. 3 and 4. The two photomicrographs are reconstructions taken from the same hologram. The subject (holographed by the Fig. 1 apparatus) was a glass 1951 resolution chart* dusted on one side with micron-sized iron carbonyl particles. For this static subject, a helium-neon laser was used to both record and reconstruct the hologram (thereby avoiding wavelength effects). The examples thus represent the ultimate product of the technique, at the chosen numerical aperture (~ 0.2).

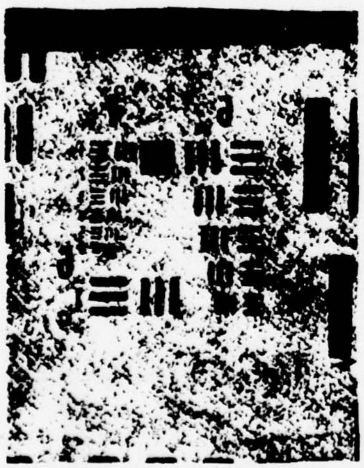

Fig. 3. Photograph of the reconstruction of a hologram of a "1951" resolution chart recorded and reconstructed with a helium-neon laser using the Figs. 1 and 2 techniques.

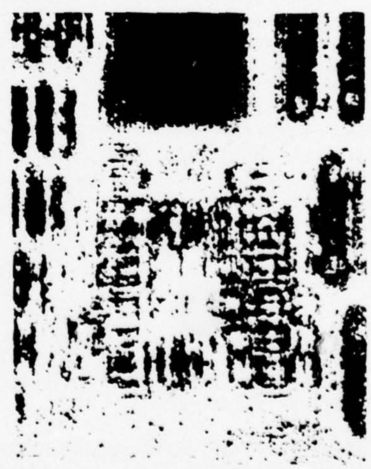

Fig. 4. Photomicrograph taken from the same hologram as shown in Fig. 3. In this case, the microscope was focused on iron carbonyl dust particles originally on the near surface of the one millimeter thick glass chart.

Figures 3 and 4 were taken through a conventional microscope set up as shown in Fig. 2. The two pictures correspond to different focal planes. In Fig. 3, the microscope was focused on the reconstructed image of the resolution chart.* No particles are seen because they are out of focus. The smallest bars have a width

* "1951" resolution charts consist of vertical and horizontal three-bar arrays whose spatial frequency (SF) varies according to the equation,

$$SF = 2^{\left\{\text{column \#} + \frac{\text{row \#} - 1}{6}\right\}}, \quad \text{line pairs per millimeter.}$$

The smallest divisions correspond to the 7th column and 6th row, a spatial frequency of 228 line pairs per millimeter (.04 in.) or bar width of 2.2 microns.

of 2.2 microns. In Fig. 4, the microscope was focused on the images of the particles originally on the near side of the (one-millimeter thick) glass supported chart. In this picture the chart images are out of focus. Particles smaller than the smallest bars in Fig. 3 can be seen, showing the ability of the technique to individually resolve (under ideal same wavelength conditions) micron-sized opaque particles. It is claimed by the authors that such resolutions are the highest achieved to date holographically![9]

When a ruby laser is used to record the holograms, the resolution is degraded only slightly if collimated illumination is used.[9] For diffuse illumination, resolution degrades to 6 microns, due to enhanced speckle from the wavelength difference. Highest resolutions necessitate no change in wavelength, particularly for diffuse holograms.*

In review, the relay lenses in the Fig. 1 arrangement supply a high numerical aperture, while the hologram records only the three-dimensional information. Without the relay lenses, the hologram must do both. Standard holographic glass plates are not perfect enough, and as a result alone, give (at the same object distances) resolutions of $\gtrsim$ 10 microns.[9]

III. Combustion Apparatus

To study the burning of solid rocket ruels at high pressures, a steel windowed combustion bomb was placed between the inverting and relay lenses of the (Fig. 1) lens-assisted holographic arrangement. The setup is diagrammed in Fig. 5. The combustion bomb had an internal diameter of 50 millimeters (2 inches), and had opposing 19-millimeter (.76 in.) thick fused quartz windows. Fuel samples (1.5 x 3 x 6 millimeter; .06 x .12 x .25 in.) were mounted on a pedestal in the center of the chamber. They were burned at pressures of 34 or 68 atmospheres of nitrogen gas. Not shown in Fig. 5 is the camera shutter ($\sim$ 5 millisecond duration), a narrow band dielectric interference filter ($\sim$ 10 Angstrom bandwidth), and red gelatin filters (Wratten #70), all of which were mounted in front of the rear viewing window. These elements reduced the flame light falling on the photosensitive plate to levels less than the transmitted laser light.

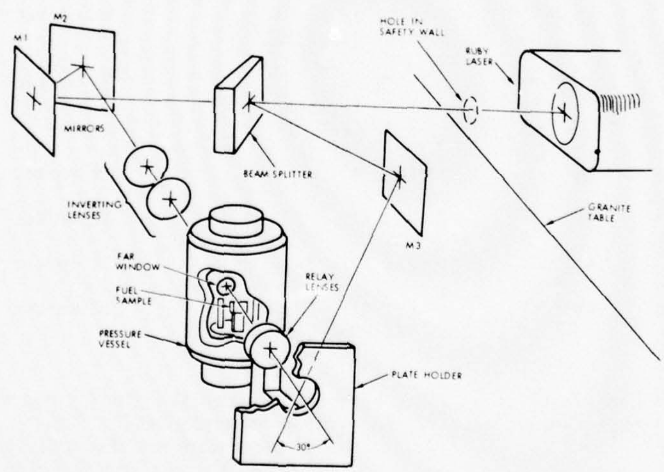

Fig. 5. Apparatus schematic showing placement of the combustion bomb, holographic components, and illuminating ruby laser.

The propellant was ignited by a hot wire. Initiation of electrical current to the wire opened the mechanical shutter, which in turn fired the laser ($\sim$ 0.1 second into the burn).

The combustion bomb and holographic components were mounted upon a granite table in an enclosed room with safety interlocked doors. The laser, associated power supplies, controls, and pressurizing bottles were in an adjacent room. The laser beam passed through a hole between the two rooms. This arrangement afforded maximum operator safety.

IV. The Ruby Laser Illuminator

The ruby laser illuminator was built by the authors. It consisted of an oscillator with a 13-millimeter diameter by 95-millimeter long 60° ruby rod (.52 x 3.80 inches) in a one-meter long (39.4 in.) laser cavity

* The theoretical resolution (R) of any optical apparatus is: $R = \lambda/2n \sin\theta$, where θ is one-half the angle subtended at the object by the aperture, and n is the index of refraction. In microscopy $n \sin\theta$ is called the numerical aperture (NA).

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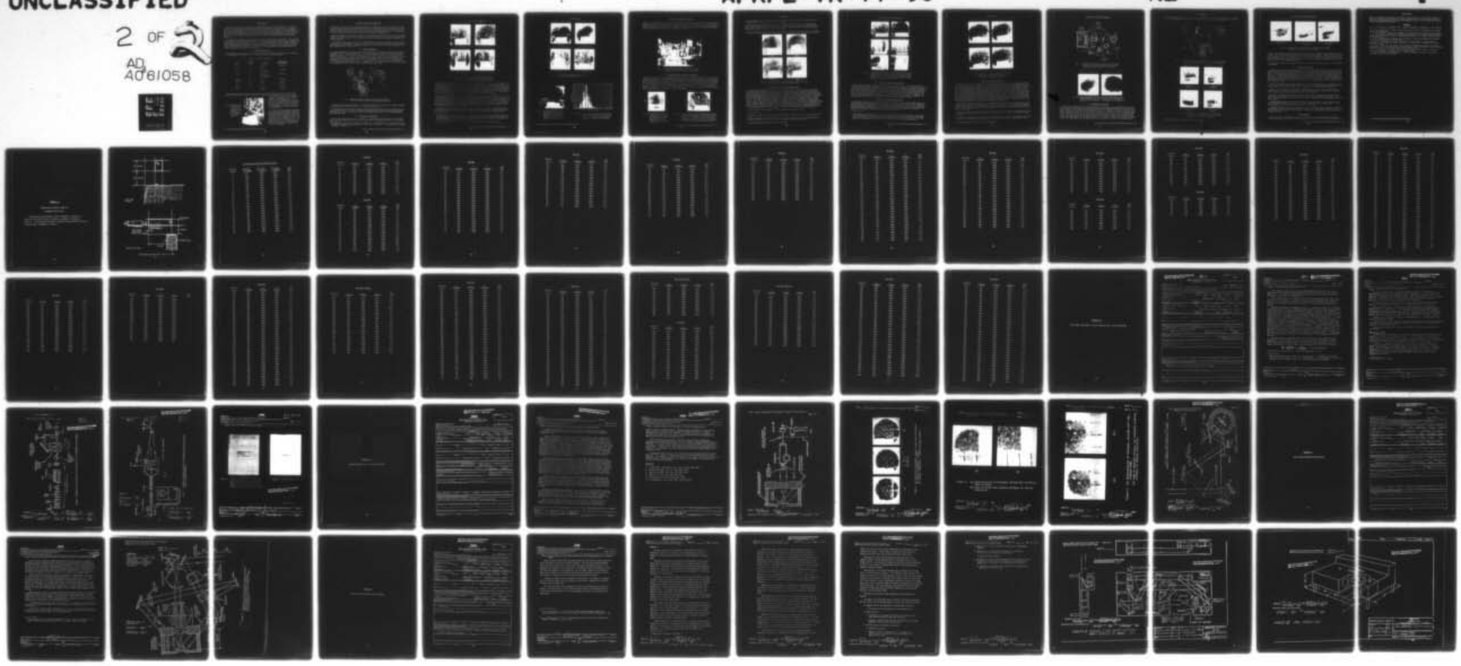

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-fined by a 99% dielectric end reflector and a double quartz etalon (the output reflector). The laser's oscillator cavity contained, in addition, two nitrobenzene Kerr cells, a calcite polarizer, and two 5-millimeter (.2 in.) diameter apertures. A second ruby rod amplified the beam's energy. With this arrangement, the laser could emit either one or two 50-80 nanosecond duration Q-switched (0.6943 micron) light pulses. The double Kerr cell arrangement could space the two pulses as closely as one microsecond. Total laser energy was 1/2 joule. After amplification, the laser beam was expanded by a Galilean telescope to 4 cm (1.46 in.) diameter. As shown in Fig. 5, the beam passed through a hole in the laboratory wall to the holographic apparatus.

The duration of a single Q-switched pulse could be further reduced with a "pulse chopper." This unit was placed between the laser oscillator and amplifier. It consisted of a half-wave plate, a laser triggered spark gap, Pockel cell, and calcite polarizing prism. With these added components, only a 10-nanosecond portion of the oscillator (nominal 50 nanosecond) pulse passed through the pulse chopper to the amplifier. The pulse chopper reduced the total laser energy ~ 1/10 joule, which was still enough to record holograms, but barely enough to compete with the fogging of the plate (due to longer development time, the present mechanical shutter, and the optical filters) by metallized fuels.

V. Single Exposure Results

A wide selection of propellant types was recorded under both collimated and diffuse modes of illumination. The chosen propellants are listed in Table I along with some of their basic properties

Table 1. The Solid Propellants

Type	Solids (AP)	Contents	Burn Rate at 68 Atmospheres
NT-10	87%	0.5% ZrC 0.5% C	13 mm/sec
MS-23	87.5%	1.0% Zr 0.5% Graphite	14 mm/sec
MX-70	87%	15.75% Al 3.0% Ferrocene 0.75% FeF_3	43 mm/sec
ANB-3066	88%	18% Al	9 mm/sec
NB-79	88%	20% Al	11 mm/sec
NB-122	90%	21% Al	4 mm/sec
NB-123	90%	21% Al 15% HMX	12 mm/sec

We began recording combustion under collimated illumination since earlier studies had shown that this type of illumination gave the highest resolutions.[9] An example is presented in Fig. 6. It is a photomicrograph of the reconstructed image taken through a microscope with a 10X - 0.3 NA objective, as diagrammed in Fig. 2. The mottled or cellular appearance of the field was due to the refraction of the collimated laser light by thermal cells set up by the burning propellant. In spite of this fault, the reconstructed image could be viewed to ~ 2 micron limits.

Fig. 6. Photomicrograph of the reconstruction of a collimated light hologram of the combustion of MS-23 propellant at 34 atmospheres.

All collimated light propellant recordings were found to show (to greater or lesser extent) severe refraction effects. For higher pressures and the more metallized fuels, the refraction by the thermal cells all but masked the particulate. Examples for some of the different fuels are presented in Fig. 7. The upper left picture in this group is a less magnified view of Fig. 6. The lower pair of pictures were 10 nanosecond exposures made with the pulse chopper.

of 2.2 microns. In Fig. 4, the microscope was focused on the images of the particles originally on the near side of the (one-millimeter thick) glass supported chart. In this picture the chart images are out of focus. Particles smaller than the smallest bars in Fig. 3 can be seen, showing the ability of the technique to individually resolve (under ideal same wavelength conditions) micron-sized opaque particles. It is claimed by the authors that such resolutions are the highest achieved to date holographically![9]

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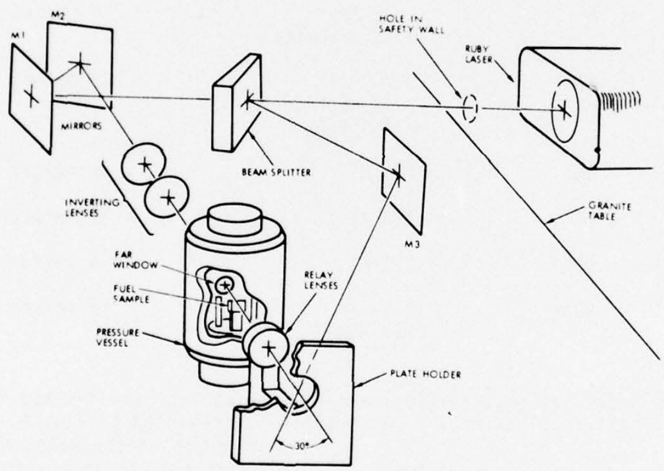

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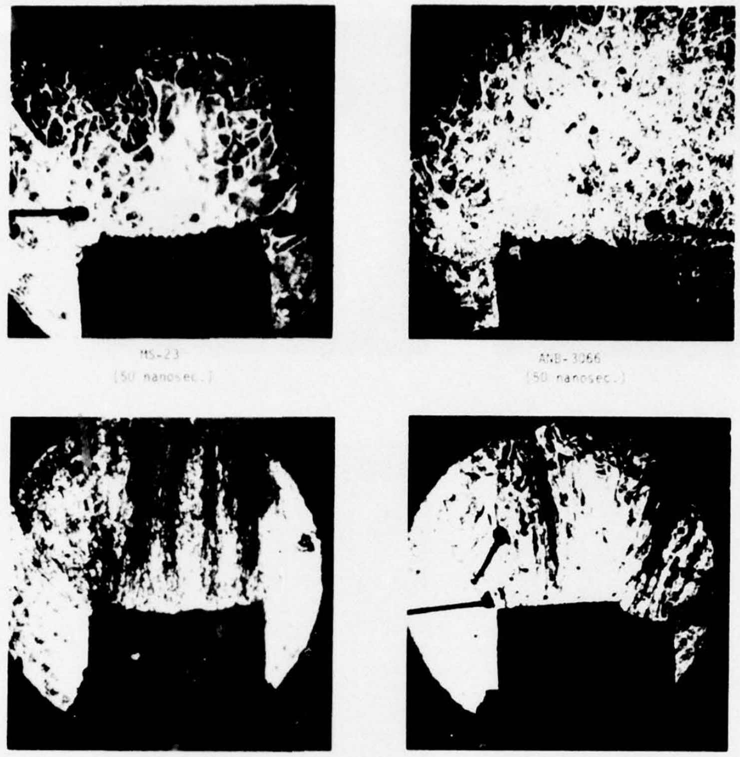

Fig. 7. Examples of selected collimated light holograms. Each was taken at 34 atmospheres of pressure. The upper pair was recorded with a laser pulse of 50 nanosecond duration. The lower pair was recorded with 10 nanosecond pulses.

Diffuse light holograms did not show significant thermal cell effects! This was due to the fact that the illuminating light was scattered continuously over a wide range of angles by the ground glass diffuser. As a result, the thermal cells were averaged. Particulates were not hidden. As noted, these holograms did not have the resolution of the collimated light holograms. Resolution was degraded to ~ 6 microns by enhanced speckle effects due to the fact that reconstructions were made with a continuous wave helium-neon laser.*,** In spite of these present limitations, diffuse light holograms were better for recording and studying particulate. A complementary set of pictures of diffuse light holograms is presented in Fig. 8. To record these holograms, a piece of ground glass was laid against the far window of the combustion bomb.

One diffuse light hologram was chosen for careful analysis. A photograph is presented in Fig. 9. An arbitrary volume--0.20 millimeter wide by 0.225 millimeter high, and 12.7 millimeter deep (.008 x .009 x .508 in.), 0.66 millimeters (.0264 in.) above the reconstruction of the burning region--was chosen (starting at the mid-plane of the propellant). All particles were located (assigned x, y, and z coordinates) and measured. A total of 568 particles were found. Counting was manual, as described earlier in Section II, and took eight working days! One representation of the data is presented in Fig. 10. It is a particle size distribution. The cross-hatched area shows where particles are competing with laser speckle effects. Beyond the cross-hatched region, the data are completely reliable.

Particle sizing in the region of speckle was greatly facilitated by the use of a moving viewing screen. The moving screen reduced the perceived speckle by about 30% and seemed to extend the resolution of diffuse light holograms down to ~ 4 microns. The data plotted in Fig. 10 were taken with the apparatus shown

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* A doubled YAG laser would be a better choice. This laser system emits 0.53 micron Q-switch pulses, and has a continuous wave version. Holograms recorded with such a laser could be reconstructed without any change in wavelength. Resolution of such diffuse light holograms should be 3 microns. Such lasers are more expensive than ruby lasers by at least a factor of two.

** As noted, a rotating translucent screen suppressed speckle enough to improve resolution to 4μ.

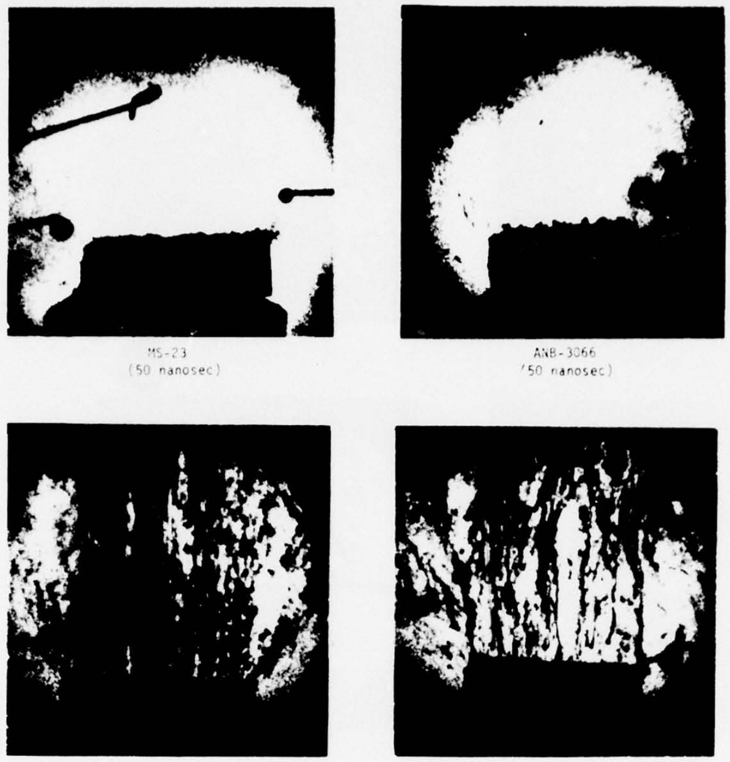

Fig. 8. Same fuels and conditions as shown in Fig. 7 except under diffused illumination.

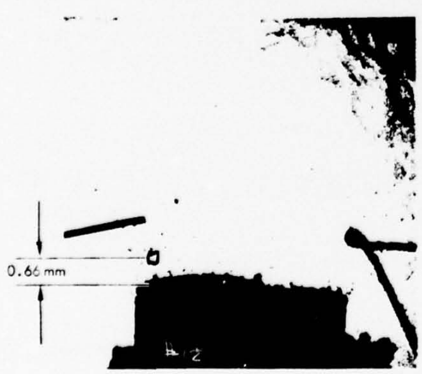

Fig. 9. Photograph of the reconstruction of MX-70 fuel at 34 atmospheres. All particles in the 3-D volume marked by the box were counted out from the centerline of the propellant.

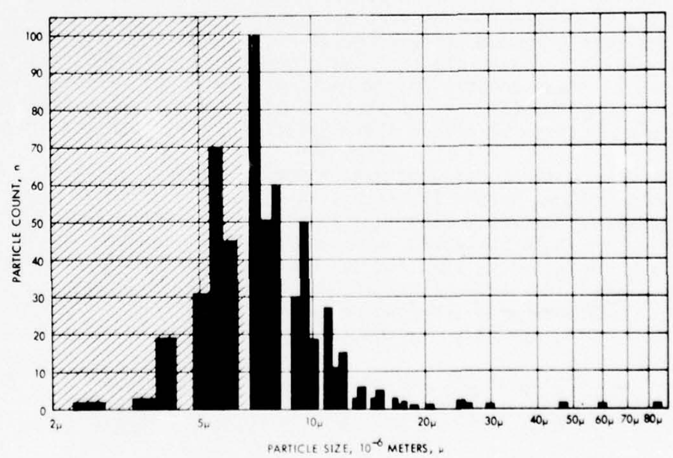

Fig. 10. Particle size distribution (568 particles) taken from arbitrary 0.20 x 0.25 x 12.7 mm (.008 x .01 x .508 in.) volume of image reconstructed from the Fig. 9 hologram.

in Fig. 11. The pseudoscopic 3-D image was formed beyond the replaced window position. The sample volume was defined by cross hairs strung on a washer. The particle images were relayed by a microscope objective onto a translucent mylar screen attached to a rotating wheel. The image was then viewed with a second microscope that had a travelling cross-hair eyepiece. Rotation of the mylar screen reduced the speckle and general eye fatigue. Dial indicators measured the relative particle positions.

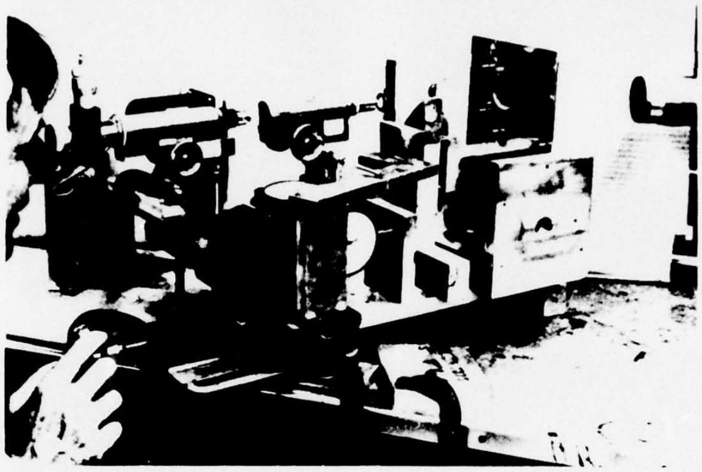

Fig. 11. Photograph of the rotating screen reconstruction apparatus used to make the Fig. 10 particle count.

VI. Conventional Double Exposure Interferograms

These are recorded in the Fig. 5 apparatus by firing the laser once prior to combustion, and then a second time during combustion.(1) On reconstruction, the two images are recreated simultaneously. Since the holographic process recreates the phase of the two scene beams, the two beams interfere with one another optically.(1) Phase differences of multiples of one-half wavelength of light cause local cancellation of the images. This cancellation is seen as interference fringes. A typical result from these studies is presented in Fig. 12. It is a photograph of the reconstruction of a double-exposed hologram of the combustion of MS-23 fuel under the condition shown in Fig. 7. The fringes highlight the thermal cells. The fringes are actually a measure of the optical path change through the illuminated volume; they give (in principle) information about the gas density variations. Such analysis is yet to be performed.

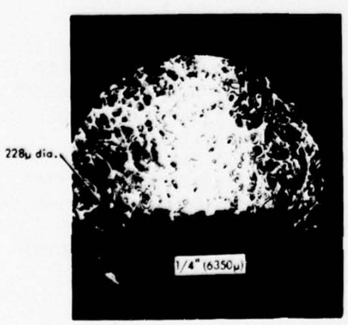

Fig. 12. Photograph of the reconstruction of a conventional double-exposed, collimated light hologram of MS-23 propellant under the Fig. 7 conditions (50 nanosecond laser pulse).

Fig. 13. Photograph of the reconstruction of a conventional double exposure holographic interferogram of NB-122 at the onset of combustion. Effects due to the heating of the background gas by the ignitor wire and propellant combustion were spatially separated in this recording (10 nanoseconds laser pulse).

One of the surprises of the study was the fact that diffuse light double exposure holograms showed no such fringe effects. This observation is not yet understood.

Another example is presented in Fig. 13. In this picture, only the left edge of the propellant had started burning at the time of the second exposure. The burning region is shown by the very fine closely-spaced fringes. The other fringes are due to the heating of the pressurized interior by the ignitor wire. Fringes around single particles can be seen on the far left.

A set of conventional interferograms which complement Figs. 7 and 8 are presented in Fig. 14. The reader should note that below the semi-image of the straight ignitor wire one sees only single exposure pictures.

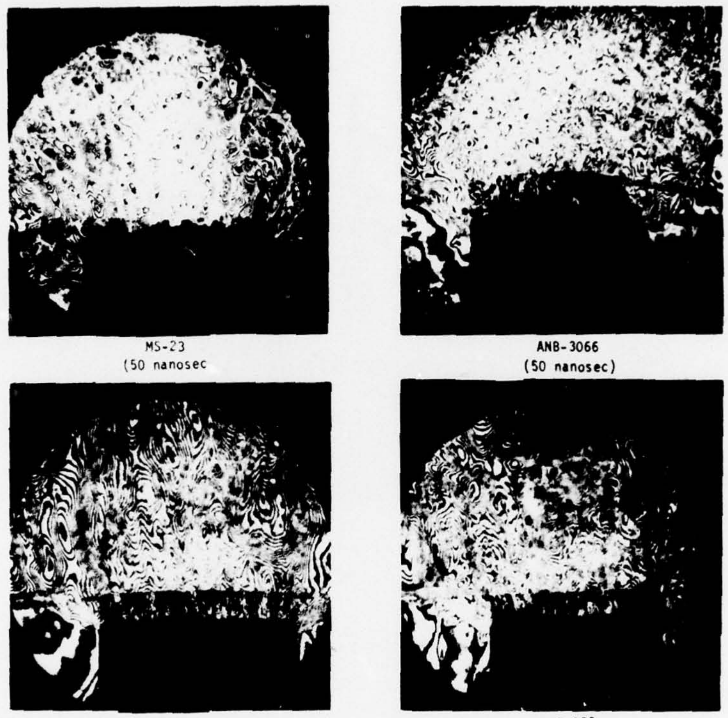

Fig. 14. Set of collimated conventional double exposure holographic interferograms complementary to Figs. 7 and 8.

VII. Laser Pulse Duration--Time Averaged Effects

The upper pair of examples in Figs. 7, 8, and 14 was recorded with conventional 50 nanosecond pulses. The lower pair of pictures was recorded with pulses of reduced duration (10 nanoseconds), via the laser-triggered spark gap. The shorter pulses were needed to avoid time-averaged interference effects due to more rapid gas expansion with the more metallized fuels. The effect is illustrated in Fig. 15, which shows both double and single exposure (collimated and diffuse) examples of NB-122 propellants recorded with conventional 50-80 nanosecond ruby laser pulses. Comparison of these pictures with those presented in Figs. 7, 8, and 14 (lower left) shows that the longer exposure pictures are characterized by regions of almost complete opacity.* This is not a dense particle effect, but instead is due to the change in optical path by the expanding gases during the longer 50 nanosecond illumination pulse. It is a holographic interference effect, in which changes in optical path greater than a quarter wavelength during the illumination period cause interference between the reconstructed images. These are seen in the reconstruction as regions of opacity or degraded contrast. As seen in Figs. 7, 8, 13, and 14, reducing the laser pulse duration results in pictures of decreased opacity as well as double exposure recordings of higher contrast interference fringes.**

Unmetallized fuels can be recorded with conventional 50 nanosecond laser pulses.

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* In addition, fringes in the double exposure example (upper right picture in Fig. 15) are essentially missing.

** Shorter illumination pulses would be even better. An ideal illuminator would be a mode-locked pulse-chopped ruby laser. Such a system would produce single 2 nanosecond duration pulses.

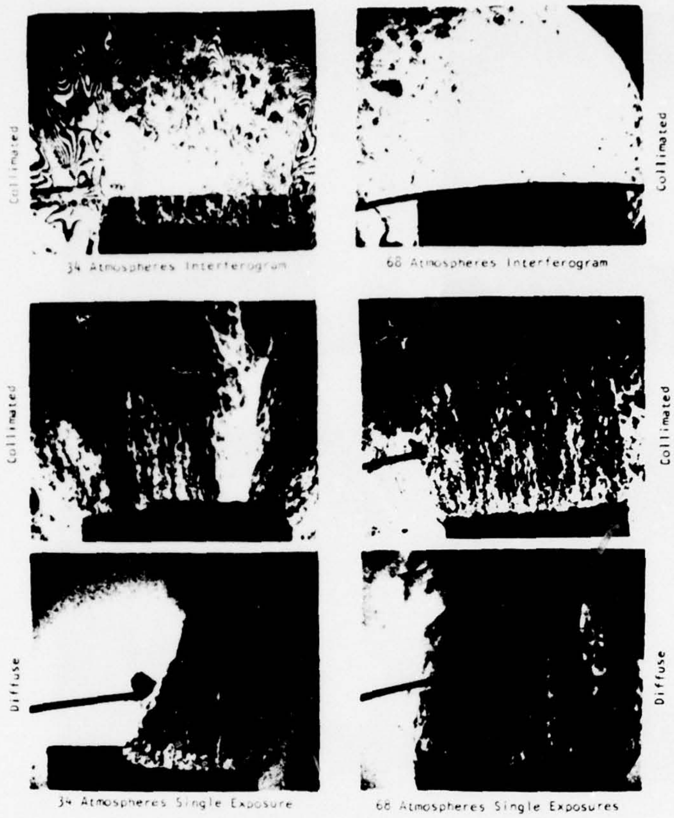

Fig. 15. Photographs of the reconstruction of holograms of combustion of NB-122 propellants recorded with 50-80 nanosecond ruby laser pulses. The pictures show time averaged interference effects due to the optical path changes by metallized fuels during the illumination period.

VIII. Rapid Double Exposure Interferograms

Double exposure holographic interferometry offers another variation, namely, the recording of the first exposure during the burning of the propellant. The second exposure is recorded a short time afterwards.* One then has, on reconstruction, a differential interferogram. Such interferograms were attempted. In general, they showed no fringes around the individual particles, indicating that the particles were in thermal equilibrium with the combustion environment. A set for MX-70 propellant for increasing spacing between the two pulses (3, 6, 12, and 18 μseconds) is presented in Fig. 16. The pictures show both particulate and interference fringes which increase in complexity as the interval between the two laser pulses increases. The particulate become less evident as the interval between the two laser pulses increases. Furthermore, the fringes become more subtle. At 100 μsecond separation, the fringes are too fine to see.

IX. Rapid Double Exposure Particle Holograms

The two upper pictures in Fig. 16 show particulate. Furthermore, it is not certain whether some of the pairs are not, in fact, double images of the same particle? If this were the case, one could compute velocities by dividing the measured displacement by the known laser pulse separation. Under such an assumption, some rather fantastic velocities can be estimated. Considerable uncertainty exists as to which two images are to be connected, or whether a given particle image has, in fact, moved between the two exposures. To eliminate such confusion, a new holocamera was constructed and tested.

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* As noted earlier in Section IV, our ruby laser illuminator had two intercavity Kerr cells. These were used to double pulse the laser. Separation between the two pulses could be continuously varied between one to 400 microseconds. Each laser pulse was 50 nanoseconds. Shortening both the pulses to 10 nanoseconds was impossible due to the millisecond recovery time of the laser-triggered spark gap.

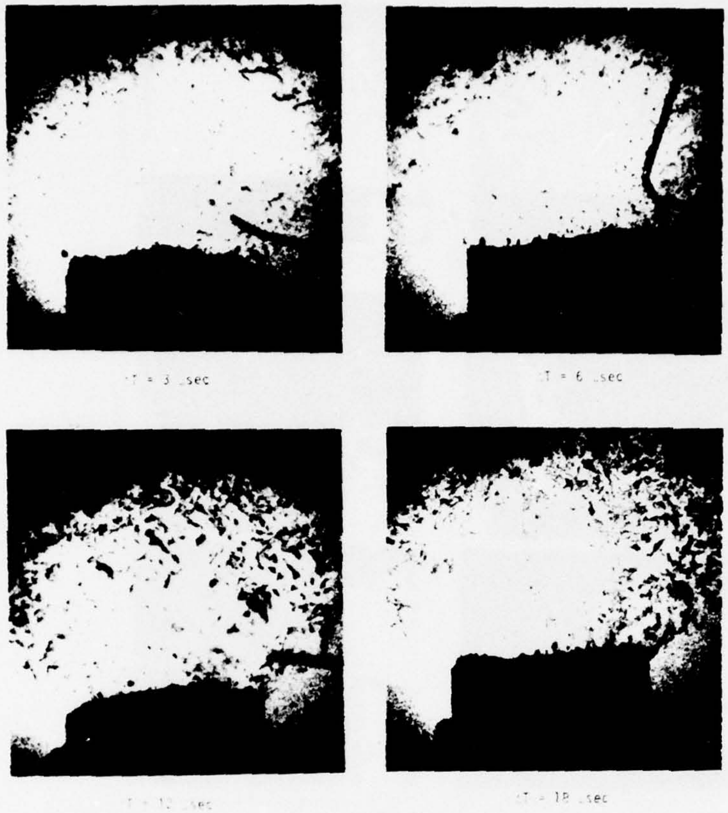

Fig. 16. Rapid double exposure interferograms of MX-70 propellant (34 atmospheres) for increasing separation ΔT between the two pulses.

X. Double Reference Beam Holocamera

The previous section at least demonstrated that double exposure holography offers a unique way of determining the velocity of small particulate. As seen in Fig. 16, single reference beam double-exposed pictures have little certainty about the particle motions, particularly when the field is fairly dense. Instead, one would like images that could be separately reconstructed. This need or requirement was realized by the construction of a holocamera with two reference beams. In actuality, the Fig. 1 or 5 apparatus was provided with a second reference beam. The new arrangement is shown in Fig. 17. After the beam splitter, an optical switch (Pockel cell and beam splitting polarizer) chose one of two reference beam paths. The Pockel cell was electrically switched to its half-wave voltage between the two laser pulses. As a result, the second light pulse was diverted along the second reference beam path. A quartz half-wave plate in this path repolarized the second laser pulse so that it was parallel and coherent with the scene laser pulse. With this arrangement, each pulse of the laser is recorded as a hologram of a spatially different reference beam. Both holographic images are recorded on the same film plate (i.e., on top of each other). However, unlike the single reference beam holograms, the two images can be independently reconstructed.

Reconstruction is as before (as per Fig. 2), except that two counter-propagating reference beams are now directed through the plate. One beam reconstructs one of the images. The other beam from the second angle reconstructs the second. Now the two images can be played back in sequence. Individual particle images can be seen to jump. Their displacements can be measured, and their velocities unquestionably computed from the known pulse separation.

A pair of pictures taken from such a recording is presented in Fig. 18. Analysis of the holographic image showed that the particles were, in general, moving in all directions with speeds on the average of 6 meters per second.

The multiple reference beam technique could be easily extended to at least two more frames. For laser pulse separations of 10 microseconds, such a holocamera would have an effective 100,000 frame per second rate.

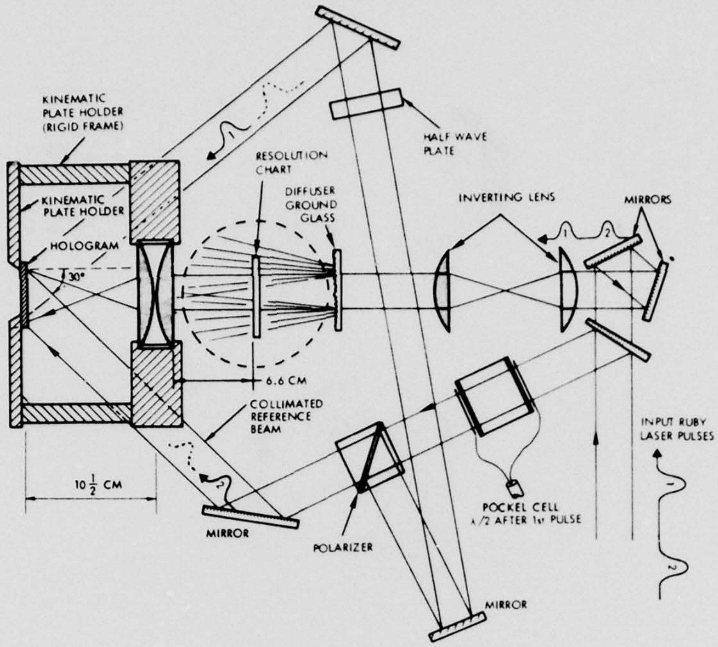

Fig. 17. Schematic of new lens-assisted double reference beam holocamera for recording separately reconstructable rapid double exposure images on a single plate.

Fig. 18. Images independently reconstructed from a double reference beam hologram recorded in the Fig. 17 apparatus with laser pulses separated by 10 microseconds. MX-70 propellant at 34 atmospheres.

XI. Reflected Light Holograms

Reflected light holograms were also attempted under the present study. They were recorded with the holographic apparatus shown in Fig. 19. Here the scene beam directly illuminated the side of the propellant and the space above. Light scattered from both passed through a side window onto the hologram. Assisting lenses were not employed since resolution was not a major consideration. Photographs of some selected reconstructed images are presented in Fig. 20. The reconstruction shows the propellant surface as well as the particulate clouds. Individual particles can be seen by their own scattering of laser light. From a holographic point of view, this type of recording is more demanding since to be recorded, the particles have to be stationary to less than a wavelength during the laser pulse duration. At speeds of $\sim$ 6 meters (over 18 feet) per second (and the net viewing angles), the holographic optical path condition is just met for 50 nanosecond pulses.

Scattered light holograms have the feature of visualizing particle clouds when the particulate is submicron in size. Furthermore, the recordings are not subject to time-average gas density effects.

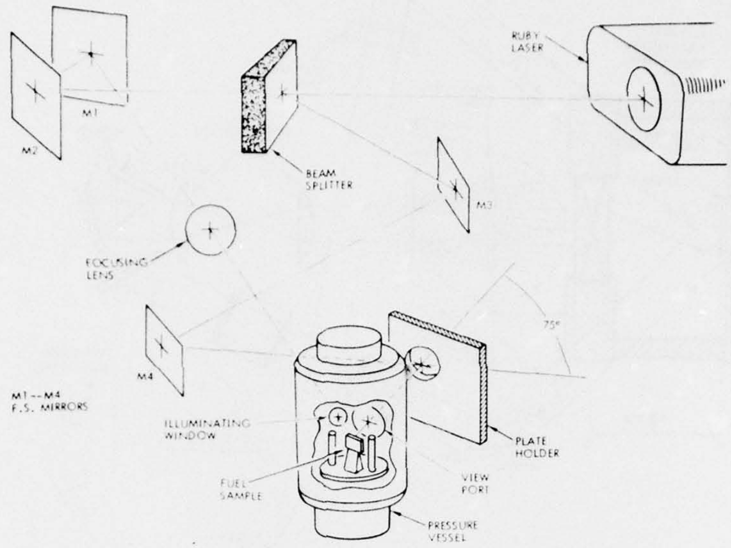

Fig. 19. Schematic of holographic arrangement used to test the feasibility of recording scattered light holograms of burning propellants.

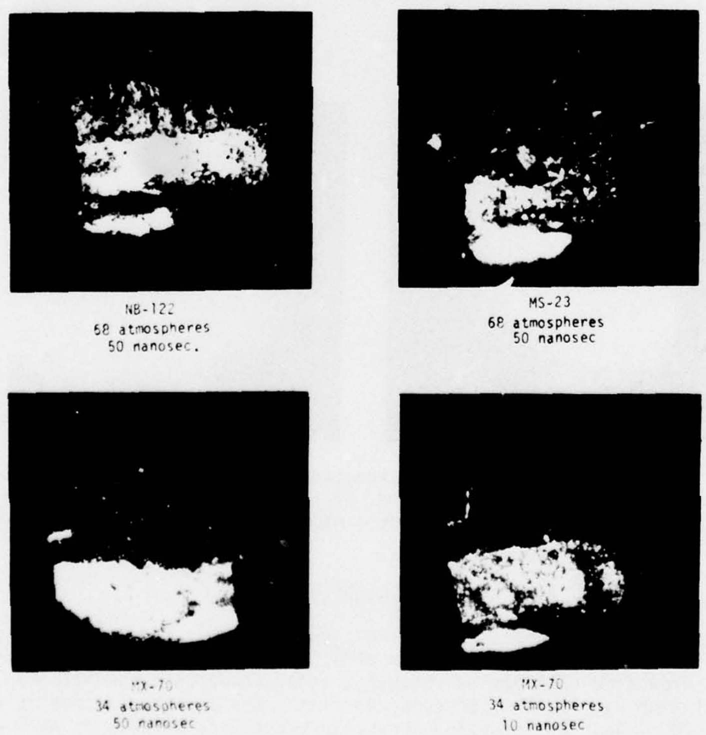

Fig. 20. Photographs of the reconstruction of some typical reflected light holograms of burning propellants recorded with the Fig. 19 arrangement.

Before Firing | 34 atmospheres 50 nanosec | 68 atmospheres 50 nanosec

Fig. 21. Photographs of the reconstruction of reflected light holograms on ANB-3066, emphasizing the burning surface.

Another motivation for the reflected light holography studies was the possibility of recording the burning surface. This was complicated by obscuration of the surface by particle clouds. However, by cutting the propellant surface on a bias, the burning surface could be visualized. Photographs of some hologram reconstructions are presented in Fig. 21. In general, not too much detail could be seen. We believe that this was due to the fact that the burning propellant surface itself is liquid and relatively transparent to the ruby laser light. As a result, the surface appears ethereal.

Reflected or scattered light holograms offer another interesting and informative way of visualizing combustion phenomena.

XII. Summary and Conclusions

A lens-assisted transmission holographic apparatus has been successfully used with a ruby laser to record three-dimensional information about the combustion of small propellant samples at high pressures ($\lesssim$ 68 atmospheres). The holograms were reconstructed with eye-safe helium-neon lasers. Collimated illumination of the combustion environment gave reconstructions with 2 micron resolutions. Thermal cells severely refracted the laser light. Diffuse rear-lighted reconstructions gave resolutions of 6 microns due to enhanced speckle effects due to the wavelength difference between the ruby and helium-neon lasers. Viewing the projected holographic images with a moving screen improved resolution by 30%, or to 4 microns. Particle size distributions were obtained manually from the hologram by measurement of the 3-D position and size of the individual reconstructed particle images.

Laser pulse durations shorter than the conventional 50 nanosecond Q-switch pulses are required with metallized propellants to avoid time-averaged interference effects. A laser-triggered spark gap pulse chopper was used to reduce the ruby laser pulse duration to $\sim$ 10 nanoseconds. Even shorter pulses are desired.

Particle velocities were measured from double exposed holograms in a special holocamera with separate reference beams. Each pulse was routed along a separate reference beam path. The two images can be reconstructed separately, avoiding any confusion about the particle motions.

Holographic interferograms could also be recorded. Conventional (first expsoure prior to combustion) double exposure holographic interferograms could be recorded only with collimated interferograms. Rapid double exposure interferograms could be recorded with diffuse illumination with pulses separated by less than 100 microseconds.

Reflected light holograms could also be recorded with 50 nanosecond pulses. These showed particles by their scattering of the laser light as well as the burning surface when it was viewed obliquely. Surface detail was poor due to the transparency of the surface to laser light?

In summary, it was found that laser holography can acquire microscopic quantitative data on the combustion characteristics, particle sizes, particle velocities, thermal cells and gas density variations of small burning solid rocket propellants at high pressures. The technique should be applicable to a wide variety of combustion phenomena.

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0059). We particularly want to thank Dr. D. George, Technical Monitor, for his interest and contributions. We want to acknowledge the contribution of Dr. Lee O. Heflinger (TRW) and Scripps Institute of Marine Resources in the development of the lens-assisted holocamera.(8) Finally, we wish to thank Betty Jackman (TRW) for preparation of the manuscript.

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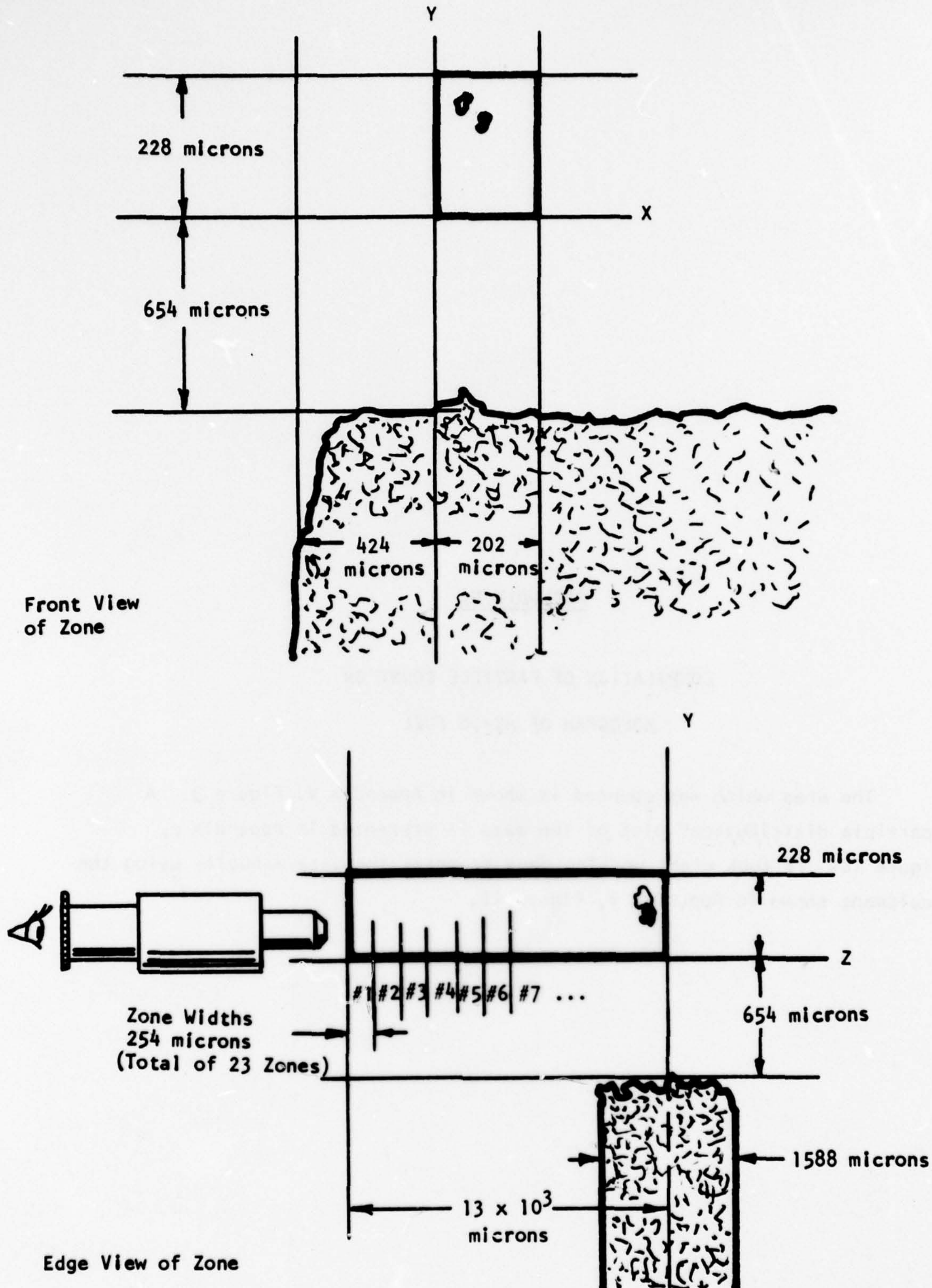
APPENDIX VI

COMPILATION OF PARTICLE COUNT ON HOLOGRAM OF MX-70 FUEL

The area which was counted is shown in Appendix V, Figure 9. A "particle distribution" plot of the data is presented in Appendix V, Figure 10. It took eight working days to amass the data manually using the equipment shown in Appendix V, Figure 11.



Zone Count Locations (Ref: Fig. 9, p. 100).

1st Zone 12.7 mm from Silhouette Surface

Particle #	Position Z (inches)	Position Y (inches)	Position X (inches)	Size (μ)
1	.001	.0010	.0230	9.5
2	.000	.0009	.0238	5.5
3	.000	.0014	.0238	6.0
4	.006	.0013	.0241	7.0
5	.006	.0023	.0257	5.5
7	.016	.0021	.0215	9.0
8	.016	.0026	.0205	6.0
9	.015	.0027	.0221	7.0
10	.015	.0028	.0229	7.0
11	.015	.0030	.0271	6.0
12	.015	.0042	.0241	7.0
13	.011	.0041	.0205	7.5
14	.005	.0047	.0244	7.0
15	.008	.0050	.0227	5.5
16	.007	.0052	.0220	9.5
17	.007	.0054	.0247	5.5
18	.008	.0056	.0240	7.0
19	.007	.0060	.0256	2.0
20	.017	.0069	.0263	9.5
21	.015	.0075	.0264	11.0
22	.003	.0075	.0247	9.5
23	.002	.0078	.0234	8.0
24	.002	.0082	.0238	6.0
25	.012	.0084	.0240	5.5

2nd Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
26	.033	.0011	.0221	5.5
27	.035	.0011	.0244	7.5
28	.038	.0013	.0269	17.5
29	.037	.0017	.0251	8.0
30	.026	.0025	.0251	8.0
31	.025	.0023	.0243	8.0
32	.023	.0028	.0221	11.0
33	.028	.0047	.0221	9.5
34	.028	.0050	.0252	10.0
35	.027	.0050	.0223	5.5
36	.027	.0053	.0226	7.0

3rd Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
37	.052	.0010	.0228	8.0
38	.045	.0019	.0230	9.5
39	.053	.0022	.0262	9.5
40	.060	.0021	.0228	5.5
41	.050	.0020	.0223	5.5
42	.042	.0024	.0209	5.5
43	.041	.0026	.0219	5.0
44	.053	.0028	.0252	10.0
45	.058	.0027	.0272	7.0
46	.055	.0036	.0238	9.5
47	.055	.0043	.0233	7.5
48	.056	.0043	.0206	8.0
49	.053	.0060	.0217	10.0
50	.051	.0064	.0225	9.0
51	.049	.0077	.0235	8.0
52	.045	.0079	.0257	7.0
53	.043	.0083	.0264	7.0

4th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
54	.077	.0005	.0237	8.0
55	.077	.0004	.0244	7.5
56	.076	.0005	.0216	5.5
57	.076	.0008	.0205	7.0
58	.060	.0015	.0275	9.0
59	.058	.0013	.0225	7.0
60	.076	.0014	.0202	6.0
61	.066	.0020	.0203	4.0
62	.066	.0020	.0208	4.0
63	.066	.0021	.0246	7.0
64	.067	.0023	.0243	9.0
65	.066	.0029	.0245	7.5
66	.066	.0031	.0240	8.0
67	.066	.0038	.0240	5.0
68	.067	.0037	.0235	7.0
69	.066	.0036	.0215	7.5
70	.066	.0034	.0204	7.0
71	.065	.0041	.0216	7.5
72	.079	.0041	.0222	7.5
73	.079	.0039	.0220	5.5
74	.063	.0045	.0207	5.5
75	.070	.0054	.0237	7.5
76	.074	.0053	.0238	7.0
77	.063	.0066	.0236	7.5

5th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
78	.093	.0081	0247	15.0
79	.098	.0017	0221	8.0
80	.099	.0021	0204	4.0
81	.103	.0004	0203	11.5
82	.111	.0010	0224	7.0
83	.109	.0004	0224	7.0
84	.105	.0009	0213	8.0
85	.104	.0021	0248	9.0
86	.110	.0027	0248	9.5
87	.118	.0034	0223	12.0
88	.105	.0039	0250	9.5
89	.117	.0040	0272	11.0
90	.112	.0039	0267	11.0
91	.115	.0035	0214	7.0
92	.105	.0064	0245	11.0
93	.111	.0078	0245	9.5
94	.112	.0077	0234	9.5

6th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
95	.124	.0007	.0206	7.5
96	.139	.0021	.0220	9.5
97	.140	.0017	.0210	6.0
98	.141	.0010	.0223	5.5
99	.131	.0018	.0212	5.5
100	.131	.0029	.0212	9.5
101	.124	.0046	.0259	10.0
102	.119	.0049	.0244	9.0
103	.124	.0055	.0229	6.8
104	.123	.0063	.0236	6.0
105	.135	.0064	.0246	7.0
106	.120	.0069	.0265	9.5
107	.118	.0078	.0264	5.5
108	.118	.0080	.0258	5.5
109	.118	.0076	.0252	5.0
110	.118	.0076	.0244	5.0
111	.123	.0079	.0251	5.0
112	.123	.0081	.0235	8.0
113	.129	.0079	.0223	5.5

7th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
114	.150	.0008	.0215	8.0
115	.149	.0011	.0222	9.0
116	.147	.0017	.0210	12.0
117	.142	.0023	.0216	7.5
118	.144	.0025	.0243	8.0
119	.147	.0029	.0258	7.5
120	.146	.0030	.0252	7.0
121	.146	.0030	.0245	7.0
122	.152	.0037	.0231	5.5
123	.150	.0044	.0245	6.0
124	.150	.0042	.0219	9.0
125	.147	.0063	.0205	10.0
126	.153	.0061	.0220	6.0
127	.155	.0070	.0212	8.0
128	.147	.0085	.0212	8.0

<u>8th Zone</u>

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
129	.160	.0005	.0228	7.0
130	.160	.0004	.0233	4.0
131	.162	.0009	.0256	3.5
132	.164	.0007	.0224	11.0
133	.164	.0018	.0196	9.5
134	.179	.0012	.0252	9.5
135	.164	.0008	.0255	7.0
136	.168	.0016	.0243	8.0
137	.175	.0015	.0209	5.5
138	.175	.0014	.0216	4.0
139	.177	.0017	.0228	7.5
140	.169	.0015	.0205	8.0
141	.174	.0015	.0210	7.5
142	.176	.0014	.0216	5.5
143	.176	.0017	.0228	7.0
144	.164	.0022	.0212	9.5
145	.169	.0025	.0223	4.0
146	.167	.0024	.0251	7.0
147	.168	.0022	.0259	9.0
148	.170	.0026	.0250	7.0
149	.175	.0026	.0232	5.5
150	.173	.0035	.0233	11.5
151	.167	.0055	.0259	7.0
152	.161	.0057	.0219	10.0
153	.158	.0061	.0198	7.0
154	.158	.0066	.0194	7.5
155	.174	.0066	.0208	7.5
156	.171	.0077	.0258	9.5
157	.156	.0080	.0242	8.0
158	.163	.0082	.0261	5.0
159	.164	.0084	.0250	7.0
160	.161	.0103	.0213	8.0

9th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
161	.180	.0002	.0219	8.0
162	.180	.0009	.0258	8.0
163	.181	.0006	.0212	7.0
164	.181	.0004	.0202	5.5
165	.200	.0002	.0215	7.5
166	.200	.0002	.0225	14.5
167	.194	.0004	.0244	11.0
168	.187	.0007	.0264	7.5
169	.180	.0011	.0227	5.0
170	.180	.0015	.0235	9.0
171	.176	.0016	.0220	5.5
172	.179	.0017	.0241	4.0
173	.178	.0031	.0212	11.5
174	.188	.0026	.0215	6.0
175	.187	.0031	.0201	6.0
176	.185	.0029	.0242	7.5
177	.193	.0031	.0208	5.5
178	.197	.0066	.0208	6.0
179	.188	.0059	.0210	9.0
180	.179	.0066	.0239	5.5
181	.180	.0074	.0234	6.0
182	.182	.0077	.0216	9.5
183	.196	.0057	.0260	7.0
184	.199	.0083	.0241	7.0
185	.199	.0083	.0232	5.0
186	.199	.0083	.0218	5.0

10th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
187	.206	.0006	.0200	5.5
188	.212	.0003	.0212	7.5
189	.209	.0013	.0234	7.0
190	.217	.0026	.0227	7.0
191	.200	.0026	.0258	7.0
192	.200	.0039	.0259	11.5
193	.205	.0077	.0252	9.5
194	.198	.0052	.0226	5.5
195	.205	.0055	.0198	9.0
196	.205	.0061	.0210	7.5
197	.209	.0069	.0212	7.0
198	.205	.0085	.0212	8.0

11th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
199	.225	.0006	.0207	5.5
200	.224	.0006	.0212	7.0
201	.236	.0010	.0223	8.0
202	.219	.0024	.0225	12.0
203	.235	.0054	.0216	6.0
204	.222	.0058	.0210	4.0
205	.233	.0081	.0229	7.0
206	.233	.0081	.0236	6.0

12th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
207	.256	.0007	.0213	7.0
208	.243	.0033	.0200	11.0
209	.251	.0043	.0213	8.0
210	.261	.0043	.0237	5.5
211	.249	.0049	.0243	5.0
212	.254	.0060	.0237	4.0
213	.243	.0066	.0254	7.5
214	.261	.0071	.0201	9.0
215	.258	.0075	.0255	9.5
216	.258	.0087	.0211	9.5
217	.245	.0075	.0251	5.5

13th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
218	.262	.0024	.0257	16.5
219	.271	.0025	.0231	7.0
220	.271	.0023	.0214	4.0
221	.259	.0044	.0258	7.5
222	.274	.0059	.0232	5.5
223	.276	.0059	.0215	7.0

14th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
224	.291	.0003	.0242	7.0
225	.285	.0021	.0214	5.5
226	.285	.0024	.0208	6.0
227	.288	.0030	.0223	5.0
228	.317	.0010	.0236	8.0
229	.316	.0017	.0246	9.0
230	.317	.0021	.0197	7.0
231	.317	.0024	.0204	7.0
232	.315	.0028	.0232	8.0
233	.318	.0039	.0233	13.0
234	.301	.0043	.0233	9.0
235	.316	.0046	.0234	17.0
236	.302	.0059	.0202	7.0
237	.302	.0061	.0238	5.0
238	.303	.0064	.0233	5.5
239	.303	.0063	.0223	5.0
240	.304	.0060	.0216	6.0
241	.304	.0065	.0206	5.5
242	.304	.0070	.0207	5.5
243	.304	.0080	.0206	7.5
244	.300	.0075	.0202	9.5
245	.310	.0085	.0253	8.0

15th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
246	.322	.0010	.0254	8.0
247	.340	.0007	.0261	5.5
248	.317	.0014	.0238	11.0
249	.316	.0005	.0245	5.0
250	.317	.0006	.0243	4.0
251	.322	.0005	.0247	5.5
252	.322	.0009	.0252	10.0
253	.325	.0013	.0221	7.5
254	.325	.0012	.0221	7.5
255	.324	.0017	.0227	8.0
256	.325	.0018	.0203	7.5
257	.336	.0020	.0205	5.5
258	.319	.0023	.0205	5.5
259	.326	.0024	.0245	7.0
260	.334	.0027	.0242	5.5
261	.327	.0030	.0240	6.0
262	.328	.0030	.0228	13.0
263	.330	.0030	.0216	6.0
264	.330	.0033	.0247	7.0
265	.324	.0039	.0208	5.5
266	.339	.0040	.0240	5.5
267	.334	.0035	.0198	15.0
268	.329	.0038	.0207	4.0
269	.332	.0041	.0209	5.0
270	.331	.0044	.0214	6.0
271	.331	.0044	.0235	5.0
272	.331	.0049	.0230	3.5
273	.337	.0047	.0199	15.0
274	.329	.0054	.0251	9.5
275	.330	.0054	.0257	7.5
276	.331	.0053	.0208	6.0
277	.331	.0057	.0218	3.5
278	.333	.0073	.0212	7.0
279	.337	.0076	.0207	7.0
280	.334	.0085	.0227	5.5
281	.334	.0089	.0208	8.0

16th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
282	.343	.0001	.0209	9.5
283	.354	.0003	.0230	9.5
284	.354	.0008	.0241	11.5
285	.347	.0006	.0235	7.0
286	.346	.0008	.0222	7.0
287	.351	.0009	.0228	5.5
288	.355	.0013	.0240	7.0
289	.355	.0014	.0246	5.0
290	.348	.0010	.0204	13.5
291	.341	.0029	.0198	8.0
292	.345	.0028	.0216	7.0
293	.338	.0035	.0249	5.5
294	.355	.0044	.0199	7.0
295	.354	.0042	.0232	8.0
296	.341	.0050	.0243	7.0
297	.341	.0049	.0234	5.0
298	.358	.0057	.0239	7.0
299	.351	.0059	.0238	7.0
300	.340	.0071	.0204	9.5

17th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
301	.366	.0003	.0240	
302	.369	.0010	.0250	
303	.378	.0013	.0222	
304	.365	.0020	.0262	
305	.366	.0043	.0242	
306	.371	.0041	.0225	
307	.378	.0048	.0264	
308	.360	.0057	.0243	
309	.378	.0062	.0205	
310	.378	.0066	.0220	
311	.380	.0071	.0216	
312	.367	.0075	.0212	
313	.369	.0078	.0244	
314	.369	.0075	.0210	
315	.369	.0079	.0224	
316	.370	.0078	.0235	
317	.375	.0086	.0212	

18th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
318	.397	.0000	.0206	7.5
319	.390	.0001	.02222	2.5
320	.397	.0002	.0237	7.0
321	.397	.0001	.0257	9.5
322	.378	.0010	.0262	11.5
323	.389	.0004	.0211	7.0
324	.390	.0008	.0205	7.0
325	.394	.0008	.0212	9.0
326	.381	.0006	.0223	5.5
327	.388	.0009	.0239	9.0
328	.396	.0008	.0215	9.0
329	.398	.0005	.0209	4.0
330	.397	.0006	.0228	5.0
331	.390	.0013	.0250	7.0
332	.399	.0012	.0224	6.0
333	.387	.0010	.0264	9.0
334	.380	.0012	.0257	3.5
335	.392	.0017	.0257	7.0
336	.380	.0020	.0230	7.5
337	.386	.0021	.0216	9.5
338	.381	.0018	.0224	3.5
339	.400	.0020	.0219	5.5
340	.401	.0019	.0229	6.0
341	.385	.0018	.0212	8.0
342	.383	.0020	.0249	9.5
343	.391	.0035	.0262	9.5
344	.381	.0027	.0204	7.0
345	.387	.0033	.0213	10.0
346	.387	.0032	.0238	4.0
347	.395	.0038	.0253	9.5
348	.384	.0035	.0215	11.0
349	.386	.0033	.0260	9.0
350	.394	.0037	.0251	7.0
351	.388	.0040	.0216	8.0
352	.388	.0040	.0223	7.0
353	.391	.0042	.0246	7.0
354	.397	.0045	.0228	7.0

18th Zone (Cont'd)

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
355	.381	.0047	.0225	7.0
356	.380	.0050	.0230	12.0
357	.385	.0053	.0261	7.5
358	.385	.0052	.0204	10.0
359	.396	.0057	.0221	26.0
360	.394	.0048	.0252	7.0
361	.399	.0052	.0254	8.0
362	.397	.0055	.0261	9.5
363	.400	.0056	.0250	7.0
364	.400	.0058	.0224	7.0
365	.395	.0056	.0211	6.0
366	.385	.0060	.0234	8.0
367	.401	.0060	.0245	8.0
368	.398	.0069	.0227	8.0
369	.392	.0073	.0242	5.5
370	.398	.0072	.0216	16.5
371	.379	.0071	.0216	6.0
372	.378	.0078	.0231	7.5
373	.393	.0079	.0218	6.0
374	.389	.0078	.0207	5.0
375	.386	.0084	.0207	13.0
376	.390	.0089	.0238	8.0

19th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
377	.405	.0002	.0204	5.0
378	.401	.0004	.0228	7.0
379	.417	.0002	.0248	8.0
380	.417	.0002	.0245	7.0
381	.400	.0005	.0227	7.5
382	.417	.0005	.0262	12.0
383	.414	.0011	.0258	7.5
384	.416	.0012	.0220	4.0
385	.402	.0016	.0224	6.0
386	.402	.0014	.0211	8.0
387	.401	.0020	.0234	5.0
388	.401	.0022	.0249	5.5
389	.399	.0022	.0200	6.0
390	.417	.0024	.0229	7.5
391	.412	.0023	.0232	7.0
392	.420	.0031	.0239	11.5
393	.420	.0031	.0255	11.0
394	.418	.0032	.0246	12.0
395	.418	.0029	.0222	5.0
396	.418	.0029	.0209	5.5
397	.418	.0037	.0250	6.0
398	.403	.0044	.0217	9.0
399	.416	.0045	.0236	6.0
400	.401	.0061	.0252	7.0
401	.401	.0059	.0223	5.5
402	.400	.0058	.0221	7.0
403	.399	.0062	.0223	12.0
404	.399	.0061	.0244	10.0
405	.414	.0059	.0248	7.0
406	.420	.0060	.0241	9.0
407	.400	.0063	.0229	9.0
408	.417	.0064	.0212	5.5
409	.401	.0066	.0236	9.5
410	.413	.0073	.0244	5.0
411	.415	.0081	.0210	5.0

20th Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
412	.435	.0001	.0211	5.5
413	.434	.0004	.0211	9.5
414	.436	.0002	.0241	4.0
415	.435	.0009	.0261	12.0
416	.428	.0007	.0227	7.5
417	.429	.0010	.0198	6.0
418	.427	.0011	.0209	14.5
419	.435	.0012	.0197	8.0
420	.435	.0013	.0203	9.5
421	.423	.0014	.0237	7.5
422	.423	.0016	.0255	7.5
423	.434	.0017	.0240	7.0
424	.431	.0020	.0218	7.5
425	.429	.0020	.0204	5.5
426	.419	.0021	.0226	10.0
427	.440	.0025	.0216	7.0
428	.418	.0025	.0208	4.0
429	.417	.0029	.0238	12.0
430	.437	.0028	.0206	7.0
431	.422	.0028	.0213	5.0
432	.431	.0030	.0261	8.0
433	.423	.0040	.0243	9.5
434	.424	.0039	.0262	7.0
435	.440	.0037	.0225	10.0
436	.431	.0037	.0214	5.5
437	.423	.0039	.0210	12.0
438	.433	.0040	.0208	5.0
439	.432	.0041	.0215	6.0
440	.421	.0047	.0232	13.5
441	.420	.0053	.0230	11.0
442	.424	.0052	.0212	3.5
443	.424	.0055	.0244	5.0
444	.420	.0053	.0257	7.0
445	.434	.0055	.0212	4.0
446	.423	.0054	.0206	6.0
447	.424	.0055	.0253	6.0

20th Zone (Cont'd)

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
448	.420	.0053	.0234	11.0
449	.423	.0056	.0246	8.0
450	.419	.0058	.0224	11.0
451	.423	.0056	.0235	11.0
452	.424	.0061	.0214	7.0
453	.424	.0063	.0205	7.5
454	.428	.0070	.0246	12.0
455	.423	.0069	.0233	5.5
456	.438	.0071	.0225	7.0
457	.439	.0074	.0211	6.0
458	.421	.0084	.0236	7.0

21st Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
459	.456	.0004	.0199	20.5
460	.450	.0002	.0251	12.0
461	.449	.0009	.0248	8.0
462	.445	.0007	.0233	8.0
463	.446	.0006	.0223	11.0
464	.444	.0005	.0218	7.5
465	.444	.0006	.0226	7.0
466	.443	.0010	.0208	7.5
467	.443	.0011	.0217	6.0
468	.441	.0017	.0259	8.0
469	.454	.0015	.0261	11.0
470	.448	.0025	.0203	9.5
471	.450	.0023	.0239	9.0
472	.458	.0026	.0250	7.0
473	.438	.0026	.0214	7.5
474	.440	.0027	.0207	8.0
475	.456	.0027	.0234	5.5
476	.456	.0035	.0218	11.0
477	.455	.0035	.0223	8.0

21st Zone (Cont'd)

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
478	.452	.0034	.0251	7.5
479	.458	.0044	.0242	9.5
480	.448	.0040	.0223	9.0
481	.453	.0036	.0218	15.0
482	.459	.0034	.0210	5.5
483	.459	.0033	.0201	5.5
484	.449	.0033	.0218	8.0
485	.449	.0042	.0235	10.0
486	.449	.0043	.0201	7.0
487	.458	.0047	.0227	5.5
488	.459	.0046	.0215	6.0
489	.443	.0052	.0219	10.0
490	.442	.0050	.0248	5.5
491	.443	.0051	.0203	9.5
492	.456	.0057	.0211	16.5
493	.451	.0064	.0239	11.0
494	.449	.0065	.0226	17.5
495	.453	.0068	.0205	7.0
496	.453	.0072	.0233	11.0
497	.448	.0076	.0252	11.0

22nd Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
498	.469	.0002	.0244	5.5
499	.469	.0005	.0251	18.5
500	.473	.0006	.0207	11.0
501	.460	.0009	.0200	11.0
502	.472	.0005	.0238	11.0
503	.470	.0011	.0239	24.5
504	.480	.0011	.0261	9.5
505	.478	.0012	.0260	9.5
506	.470	.0016	.0218	25.0
507	.476	.0028	.0222	7.0
508	.476	.0027	.0239	10.0
509	.463	.0030	.0252	13.5
510	.463	.0030	.0264	9.0
511	.465	.0030	.0210	13.5
512	.465	.0037	.0202	12.0
513	.466	.0041	.0260	9.5
514	.465	.0041	.0214	7.0
515	.468	.0042	.0224	8.0
516	.470	.0046	.0236	5.5
517	.470	.0045	.0218	7.0
518	.479	.0057	.0202	60.0
519	.459	.0047	.0214	7.0
520	.469	.0045	.0236	8.0
521	.478	.0043	.0252	11.0
522	.478	.0043	.0264	6.0
523	.474	.0057	.0225	5.5
524	.474	.0061	.0235	7.5
525	.474	.0062	.0248	5.5
526	.461	.0071	.0265	9.5
527	.467	.0085	.0263	9.0
528	.467	.0073	.0263	10.0
529	.480	.0079	.0237	11.5
530	.473	.0066	.0221	8.0
531	.473	.0068	.0232	11.5
532	.464	.0053	.0222	84.5

23rd Zone

Particle #	Z (inches)	Y (inches)	X (inches)	Size (μ)
533	.485	.0006	.0229	13.5
534	.485	.0010	.0239	9.5
535	.483	.0012	.0249	10.0
536	.490	.0010	.0236	6.0
537	.485	.0013	.0215	5.5
538	.500	.0011	.0221	11.5
539	.487	.0009	.0201	15.0
540	.490	.0017	.0232	10.0
541	.485	.0017	.0212	7.5
542	.480	.0014	.0208	8.0
543	.484	.0025	.0199	9.5
544	.485	.0023	.0219	9.5
545	.500	.0030	.0268	2.5
546	.499	.0027	.0225	6.0
547	.496	.0031	.0248	7.0
548	.491	.0035	.0203	8.0
549	.491	.0045	.0204	12.0
550	.490	.0043	.0219	5.5
551	.485	.0045	.0234	5.0
552	.489	.0050	.0219	6.0
553	.489	.0051	.0229	8.0
554	.482	.0054	.0236	4.0
555	.482	.0055	.0252	5.0
556	.484	.0056	.0270	7.5
557	.497	.0057	.0215	9.0
558	.495	.0058	.0205	11.0
559	.480	.0067	.0230	11.0
560	.500	.0066	.0248	7.0
561	.484	.0065	.0240	5.0
562	.497	.0072	.0253	5 5
563	.497	.0069	.0200	7.5
564	.497	.0075	.0199	6.0
565	.488	.0083	.0227	47.0
566	.487	.0083	.0251	9.5
567	.484	.0083	.0258	11.5
568	.485	.0078	.0261	8.0
569	.478	.0078	.0273	14.5

APPENDIX VII

PRELIMINARY EXPERIMENTS ON PULSE CHOPPING WITH A VACUUM PHOTODIODE

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TRW

DOCKET NO. 11050

NEW TECHNOLOGY REPORT FORM
(INVENTIONS & INNOVATIONS)

COMPLETE BOTH SIDES OF FORM
SEE INSTRUCTIONS, PAGE 2
MAIL TO: TRW SYSTEMS AND ENERGY PATENT COUNSEL (E2/8014)

DATE August 10, 1977

TITLE OF INVENTION/INNOVATION: VACUUM PHOTODIODE LASER PULSE CHOPPER

INNOVATOR(S)

FULL NAME (NO INITIALS)	CITIZENSHIP	BADGE NO.	S.S. NUMBER	TRW MAIL STA.	EXTENSION
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FULL NAME (NO INITIALS)	(CITIZENSHIP)	BADGE NO.	S.S. NUMBER	TRW MAIL STA.	EXTENSION
RESIDENCE (STREET)		(CITY)	(COUNTY)	(STATE)	(ZIP)
IMMEDIATE SUPERVISOR	SECTION, DEPT, LAB., DIV.		CCC	TRW MAIL STA.	EXTENSION

CONTRACT OR PROJECT (IRAD, B&P, PMP, ETC.) INFORMATION

TITLE Application of Holography to Combustion Characterization of Solid Rocket Propellants
PROJECT NUMBER
COMPLETION DATE MONTH Dec. YEAR 77
CUSTOMER USAF/Rocket Propulsion Lab
CONTRACT NUMBER F04611-76-C-0053
TRW S/N 29889
JOB NUMBER 3349-99

BACKGROUND INFORMATION

LIST JOB NUMBERS USED FOR WORK RELATED TO THE INVENTION/INNOVATION

ENGINEER'S NOTEBOOK & PAGE NUMBERS 11353, pp. 8-12 (Briones)

WHEN WAS INVENTION/INNOVATION FIRST CONCEIVED OR REDUCED TO A PRACTICE?
Not reduced to practice.

HAS INVENTION/INNOVATION BEEN SOLD OR USED IN TRW PRODUCTS? NO X YES (IF YES, WHEN? WHERE? TO WHOM?)

POTENTIAL INDUSTRIAL AND COMMERCIAL APPLICATIONS

INDICATE APPROXIMATE STATE OF DEVELOPMENT	CONCEPT	DESIGN	PROTOTYPE	MODIFICATION	IN PRODUCTION	OTHER
	X	X				

PUBLICATIONS DISCLOSING INVENTION/INNOVATION

TRW REPORTS, MEMOS AND PROPOSALS (INCLUDE DATE, NUMBER, AND TITLE)
Monthly Contract R&D Report #14, August 1977 (SN 29889)

JOURNAL ARTICLES (NAME OF PUBLICATION, DATE OF ISSUE, PAGE NUMBERS)
--

MEETING/SYMPOSIA PRESENTATIONS (SOCIETY, DATE OF PAPER, LOCATION)
--

SYSTEMS 125 REV. 12-76 PAGE 1 OVER

INSTRUCTIONS:
1. Describe problem invention innovation is designed to solve: reference similar devices.
2. Summarize what it does and how it does it. If appropriate, attach signed witnessed and dated prints, memos, reports, etc.
3. Give the advantages of the invention innovation over devices presently known.
4. List the features of the invention innovation that are believed to be novel.
5. If more space is needed, use additional copies of this form.

DOCKET NO. ______

TITLE: VACUUM PHOTODIODE LASER PULSE CHOPPER

Tests recently conducted by the authors showed (experimentally) that a bi-planar photodiode can pass enough current to discharge a Kerr cell or Pockel cell in $\lesssim$ 20 nanoseconds time. As a result, a photodiode could be used to chop or shorten the normal 50 nanosecond pulse from a Q-switched laser.

Vacuum photodiodes have the property that (unlike laser-triggered spark gaps) there are no deionizing effects. The vacuum diode should recover after each laser pulse, permitting it to chop successive pulses from a double pulsed Q-switched laser. Present gas-filled pulse choppers cannot multiple pulse in time due to the deionization time of the gap.

The new pulse chopper is exceedingly simple. It is shown in Figure 1 in relationship to a double pulsed ruby laser. A polarized light pulse from the ruby laser passes through a Kerr cell biased to its full wave retardation voltage ($\sim$ 20 kV). At full retardation light emerges from the Kerr cell with the same sense of polarization with which it entered. A polarizer (shown as a calcite prism with escape windows) diverts all of the light. As shown, the light is reflected by a 90° prism and is diverged by a negative lens. The light is reflected by a mirror onto the photocathode of an ITT bi-planar photodiode. This diode, however, as will be seen, will have been modified to give it sufficient peak current capability. The diode is attached directly to the plates of the Kerr cell. Discharging the Kerr cell reduces the retardation voltage. At half-wave ($\sim$ 14 kV) retardation, the light emerges from the Kerr cell polarized orthogonally. It passes through the polarizer into the outer world (not directed into the photodiode). One might think that interruption of light would stop the discharge of the Kerr cell. Tests, however, indicate that the photoelectric current will continue due both to space change and inductance effects. The Kerr cell voltage should be literally swept through its $\lambda/2$ wave voltage? As a result, the laser pulse will be "chopped". Only a portion of light equal in time ($\sim$ 5 nanoseconds) to the passage through the Kerr cell's half-wave voltage will pass through the diverting polarizer.

The above notion is based upon experiments conducted with some standard bi-planar photodiodes. To make a long story short, it was found that by decreasing the anode-cathode spacing of a commercial F-4000 photodiode, photoelectric currents of the order of 50 amperes could be drawn when the full output of the laser was spread across the diode's photocathode.* Such a current would discharge a 25 $\mu\mu$F Kerr cell at a rate of

$$\frac{dV}{dt} = \frac{50 \text{ amperes}}{25\ \mu\mu F} = 5\ \frac{\text{volts}}{\text{picosecond}} = 5{,}000 \text{ volts/nanosecond}$$

Full wave bias of a Kerr cell is $\sim$ 20 kV. Half wave bias is 14 kV.

---

* F4000 photodiode--product of ITT, Fort Wayne, Indiana. 4 cm diameter photocathode with 0.6 cm anode-cathode spacing (11 cm^2 cathode area). The S-1 cathode has a sensitivi sensitivity of $\sim$ 2 mA/watt. Thus, for 1 MW, it should emit 2,000 amperes.

INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE
R.A.Briones		R.F.Wuerker	4-12-77		

WITNESSED, READ AND UNDERSTOOD BY G.L.Clark, WITNESS, DATE 4-2-77; AND BY L.O.Heflinger, WITNESS, DATE Aug 17 1977

SYSTEMS 125 REV 12-76 PAGE 2

TRW

INSTRUCTIONS
1. Describe problem invention or innovation is designed to solve, reference similar devices.
2. Summarize what it does and how it does it. If appropriate, attach signed, witnessed and dated prints, memos, reports, etc.
3. Give the advantages of the invention or innovation over devices presently known.
4. List the features of the invention or innovation that are believed to be novel.
5. If more space is needed, use additional copies of this form.

DOCKET NO. ______

TITLE: VACUUM PHOTODIODE LASER PULSE CHOPPER

The current capability of a modified bi-planar photodiode was investigated experimentally with the circuit arrangement shown in Figure 2.* Light from a Q-switched ruby laser was incident upon the diode's cathode. The diode was biased by a 200 μμF capacitor. The capacitor was connected to a 50 Ω cable, terminated at a 519 oscilloscope with a 50:1 resistive divider. A typical photoelectric current pulse is shown in Figure 3; in this case, 40 amperes was reached in 50 nanoseconds.

The laser emission is shown in Figure 4. Total optical power and energy was not measured. The laser was near threshold. We estimate an emission of 1/5 joule?

More significant was the fact that the laser was mode-locked. The output was highly modulated. Inspection of Figure 3 shows that the high current photodiode barely saw the strong light oscillations. It is believed that this was due to the fact that the photodiode was operating space charge limited. Inductance effects also are believed to keep the photocurrent flowing. These effects, as noted above, should carry the diode right through the $\lambda/2$ voltage, when used in a pulse chopper like that shown in Figure 1.

Further tests are needed to perfect the photodiode chopper. A photodiode with even closer spacing would be better.

We believe that a vacuum photodiode chopper would be better than the spark gap chopper. It would, in addition, permit individual chopping of multiple pulse emission--something impossible with spark gap choppers.

Shorter laser pulses are of interest in holographic microscopy of burning rocket fuels as well.

Notes Added in Proof

The area under the photoelectric current pulse (Figure 3) gives the electrical charge passed by the diode (i.e., integral of current). This turned out to be equal to the initial charge on the capacitor (200 μμF)(20,000 volts) = 4 μcoulombs. The photodiode discharged the capacitor. This is not unexpected since the cathode sensitivity (2 ma/watt), laser power, and duration have the capability of liberating far more charge, ∿ 400 μC.

To achieve 40 amperes of photoelectric current from a standard ITT diode (0.6 cm anode-cathode spacing). The diode was heated until the glass reached the softening point. The cathode-anode distance was reduced (tube allowed to collapse). A standard photodiode (S-1 cathode) was altered without losing vacuum. The photocathode, however, looked different, and may, in fact, have been altered (higher work function). High photoelectric currents were drawn, making the authors believe that multiple photon processes were working.

* See "Notes Added in Proof."

INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE
R.A.Briones		R.F.Wuerker			

WITNESSED, READ AND UNDERSTOOD BY ______ G.L.Clark WITNESS ______ DATE AND BY ______ L.O.Heflinger WITNESS Aug 17 197? DATE

SYSTEMS 125 REV 12.76 PAGE 2)

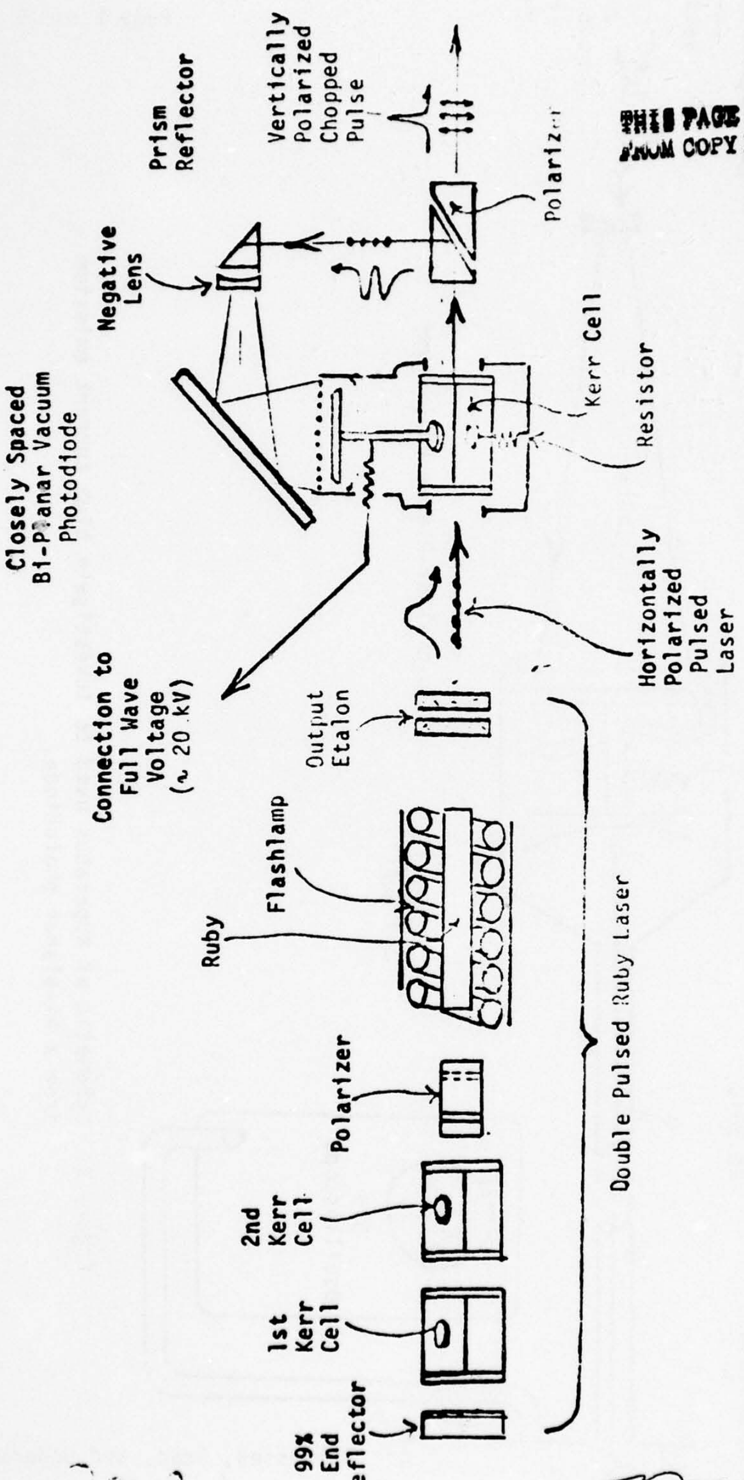


Figure 1. Schematic of Q-switched laser with bi-planar vacuum photodiode pulse chopper.

INVENTORS: R.A. Briones, Date 8-12-77 and R.F. Wuerker, Date 8-12-77

Witnessed, Read, and Understood by G.L. Clark, Date 8-12-77 and L.O. Heflinger, Date Aug 17, 77

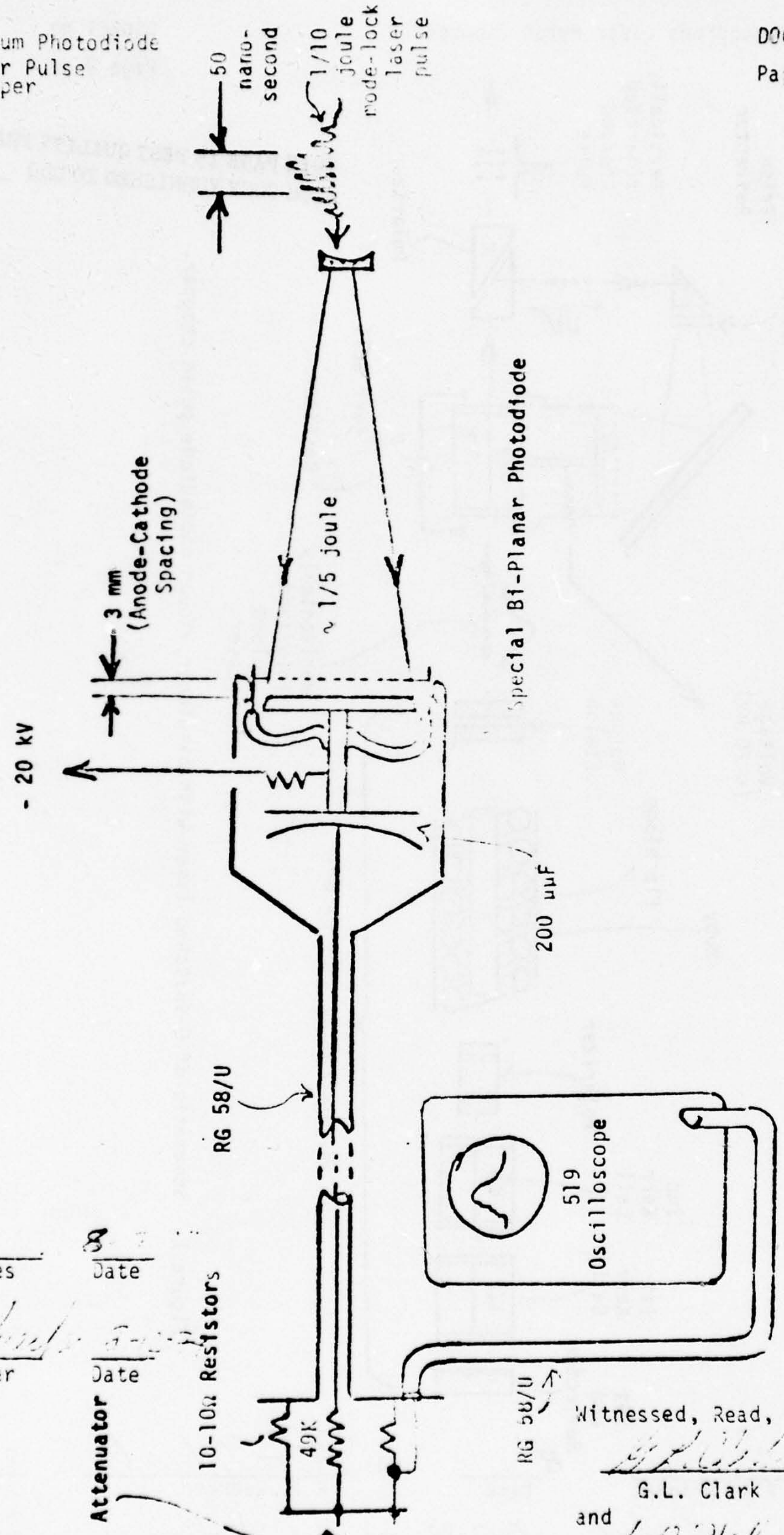


Figure 2. Schematic of apparatus used to investigate high current emission from a bi-planar photodiode.

INVENTORS:

R.A. Briones — Date

and

R.F. Wuerker — Date

Witnessed, Read, and Understood by:

G.L. Clark — Date

and

L.O. Heflinger — Date

TRW

11-050

INSTRUCTIONS

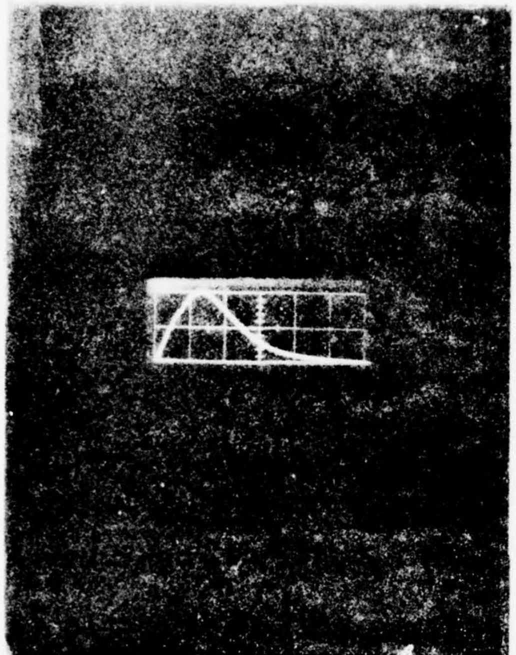
1. Describe problem invention/innovation is designed to solve; reference similar devices.
2. Summarize what it does and how it does it. If appropriate, attach signed, witnessed and dated prints, memos, reports, etc.
3. Give the advantages of the invention/innovation over devices presently known.
4. List the features of the invention/innovation that are believed to be novel.
5. If more space is needed, use additional copies of this form.

DOCKET NO.

PAGE 5 OF 5

TITLE: Vacuum Photodiode Laser Pulse Chopper

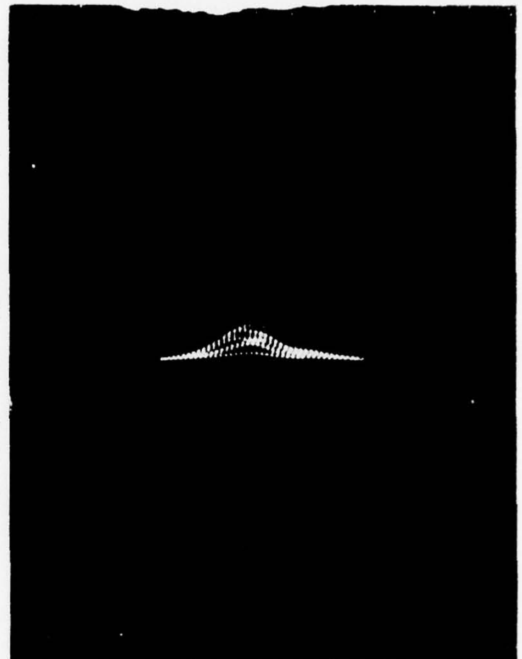
20 Amp/Div



50 Nanosec/Div

Figure 3. Typical photocurrent as a function of time (using Figure 2 circuitry). Vertical sensitivity 20 amperes/major division. Horizontal sensitivity 50 nanoseconds/major division.

Relative Laser Power (MW)



50 Nanosec/Div

Figure 4. Typical laser emission.

INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE
R.A.Briones	8-12-77	R.F.Wuerker	8-12-77		

WITNESSED, READ AND UNDERSTOOD BY B.L.Clark WITNESS — DATE 8-12-77 — AND BY: L.O.Heflinger WITNESS — DATE Aug 12, 77

SYSTEMS 125 REV. 12-76 (PAGE 2)

APPENDIX VIII

SPECKLE SUPPRESSION WITH A ROTATING DIFFUSER

DOCKET NO. 11012

TRW
DEFENSE AND SPACE SYSTEMS GROUP

NEW TECHNOLOGY REPORT FORM

(INVENTIONS & INNOVATIONS)

COMPLETE BOTH SIDES OF FORM
SEE INSTRUCTIONS, PAGE 2
MAIL TO: TRW SYSTEMS AND ENERGY PATENT COUNSEL (E2/8014)

DATE March 7, 1977

TITLE OF INVENTION/INNOVATION: Speckle Suppression of Holographic Microscopic Reconstructions

INNOVATOR(S)

FULL NAME (NO INITIALS)	(CITIZENSHIP)	BADGE NO.	S.S.NUMBER	TRW MAIL STA.	EXTENSION
Robert Albert Briones	U.S.	10525	568-40-1645	R1/1022	61370,61624

RESIDENCE (STREET)	(CITY)	(COUNTY)	(STATE)	(ZIP)
694 Cecil St.	Monterey Park,	Los Angeles	CA	91754

IMMEDIATE SUPERVISOR	SECTION, DEPT, LAB., DIV.	CCC	TRW MAIL STA.	EXTENSION
K. Yano	ATD/ESL/Laser Physics	4310	R1/1022	62757

FULL NAME (NO INITIALS)	(CITIZENSHIP)	BADGE NO.	S.S.NUMBER	TRW MAIL STA.	EXTENSION

RESIDENCE (STREET)	(CITY)	(COUNTY)	(STATE)	(ZIP)

IMMEDIATE SUPERVISOR	SECTION, DEPT, LAB., DIV.	CCC	TRW MAIL STA.	EXTENSION

FULL NAME (NO INITIALS)	(CITIZENSHIP)	BADGE NO.	S.S.NUMBER	TRW MAIL STA.	EXTENSION

RESIDENCE (STREET)	(CITY)	(COUNTY)	(STATE)	(ZIP)

IMMEDIATE SUPERVISOR	SECTION, DEPT, LAB., DIV.	CCC	TRW MAIL STA.	EXTENSION

CONTRACT OR PROJECT (IRAD, B&P, PMP, ETC.) INFORMATION

TITLE	PROJECT NUMBER	COMPLETION DATE
Application of Holography to Combustion Study of Solid Propellants	F04611-76-C-0053	MONTH 9 YEAR 77 ?

CUSTOMER	CONTRACT NUMBER	TRW S/N	JOB NUMBER
Air Force Rocket Propulsion Lab.	"	29889.000	3349-98

BACKGROUND INFORMATION

LIST JOB NUMBERS USED FOR WORK RELATED TO THE INVENTION/INNOVATION	ENGINEER'S NOTEBOOK & PAGE NUMBERS
3349-98	#11320, pg. 36

WHEN WAS INVENTION/INNOVATION FIRST CONCEIVED OR REDUCED TO A PRACTICE?

HAS INVENTION/INNOVATION BEEN SOLD OR USED IN TRW PRODUCTS? NO X YES (IF YES, WHEN? WHERE? TO WHOM?)

POTENTIAL INDUSTRIAL AND COMMERCIAL APPLICATIONS

INDICATE APPROXIMATE STATE OF DEVELOPMENT	CONCEPT	DESIGN	PROTOTYPE	MODIFICATION	IN PRODUCTION	OTHER
	X	X	X			

PUBLICATIONS DISCLOSING INVENTION/INNOVATION

TRW REPORTS, MEMOS, AND PROPOSALS (INCLUDE DATE, NUMBER, AND TITLE)
None at present, but will be reported as progress in Ninth Status Report.

JOURNAL ARTICLES: (NAME OF PUBLICATION, DATE OF ISSUE, PAGE NUMBERS)
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MEETING/SYMPOSIA PRESENTATIONS: (SOCIETY, DATE OF PAPER, LOCATION)
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TRW

INSTRUCTIONS
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2. Summarize what it does and how it does it. If appropriate, attach signed, witnessed and dated prints, memos, reports, etc.
3. Give the advantages of the invention innovation over devices presently known.
4. List the features of the invention innovation that are believed to be novel.
5. If more space is needed, use additional copies of this form.

DOCKET NO. ______

TITLE: Speckle Suppression of Holographic Microscopic Reconsturctions

A technique which reduces speckle noise and improves resolution of coherently illuminated subjects was discovered while attempting to maximize the resolution of holographic images.

Inherent in holography is a granular field noise, generally called speckle, which masks the microstructure of recorded subjects. A concentrated effort to reduce this effect has been made over the years. Leith and Upatnieks[1] introduced a diffuser in the scene beam of two-beam holography which reduced the large diffraction noise to a fine-structured speckle. For large subjects, this speckle is acceptable, but in holomicroscopy it hides fine detail. For this reason, efforts to eliminate the speckle have continued. Phase plates, gratings, double holograms, multi-color, multi-beam techniques. etc., have been tried with various degrees of success.[2-6] Not all the effort has been restricted to the recording phase. Noise reduction in reconstruction techniques has included beam dithering, or motion, extending the source area of the reconstructing beam, and using a broad spectral line width light source. In many of these efforts, speckle reduction has been accompanied by loss of resolution.

The device and technique presented here first placed a rotating fine-structured transparent diffuser through the plane of the aerial image reconstructed from a hologram (by reverse reference beam method). Because of focal depth of the examining microscope optics, the rotating diffuser was moved from the plane of the aerial image (position A) to a position between the microscope objective and the eyepiece (position B). A schematic of the system is shown in Fig. 1. Before accepting position B, a careful comparison was made to insure that no loss in resolution would be incurred. Within the limits of the available equipment, position B was the most practical position to use. With the moving diffuser in position B, a direct comparison between directly illuminated objects and holographic reconstructions of objects could be made.

A comparative series of photographs was then taken by using the eyepiece as the camera lens to focus the images onto Polaroid Type 52 film. The exposure levels were controlled by varying the time of exposure. The subject chosen was a sample of solid rocket propellant. This subject shows much structure, and its reflectivity properties range from diffuse to specular and from translucent to absorptive. A steel ruler with divisions of 1/32 inch was placed adjacently to calibrate the field (1/32 inch is 794 microns).

The first comparative set presented is shown in Fig. 2. Photomicrographs 2a and 2b show a comparison of the actual fuel sample when directly illuminated by a) white light and b) helium-neon laser light. Figure 2c then compares the difference between b) laser-lighted subject with no attempts at speckle suppression, and c) laser illuminated subject with rotating diffuser to improve resolution and suppress speckle.

For the second series of photographs, a similar sample of propellant was first holographed. A helium-neon laser was used to both record and to reconstruct the image to be photomicrographed. Figure 3a shows the photographed reconstruction

INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE
R.A.Briones	-77				

WITNESSED, READ AND UNDERSTOOD BY R.F.Wuerker 3/3/77 AND BY L.O.Heflinger -77

R.F.Wuerker WITNESS DATE L.O.Heflinger WITNESS DATE

SYSTEMS 125 REV 12-76

TRW

INSTRUCTIONS:
1. Describe problem invention/innovation is designed to solve; reference similar devices.
2. Summarize what it does and how it does it. If appropriate, attach signed, witnessed and dated prints, memos, reports, etc.
3. Give the advantages of the invention/innovation over devices presently known.
4. List the features of the invention/innovation that are believed to be novel.
5. If more space is needed, use additional copies of this form.

DOCKET NO. ______

TITLE: Speckle Suppression of Holographic Microscopic Reconstructions

with no attempt to suppress speckle. Figure 3b shows the identical system with the addition of the rotating diffuser between the eyepiece and objective. Note the increased detail and size of the field when the moving diffuser is introduced. It was only after examining Fig. 2c that it was realized that a field stop placed near the moving diffuser should have been left off.

The final comparison was made to show the relative practical differences encountered when employing holography of dynamic subjects. The problem one typically encounters is that the recording laser is not at the same wavelength as the reconstructing laser, i.e., ruby to HeNe. The hologram for the series of Fig. 4 was taken with a ruby laser. Figure 4a is the HeNe reconstructed image as seen through the microscope. Figure 4b is the photograph with the insertion of the rotating diffuser device via a translating slide.

The holograms made for Figs. 3 and 4 were made in the reflection type holocamera shown in Fig. 5. This is a holocamera used for the associated studies for the U.S. Air Force. Its complexity is due to the fact that it is just one of various holographic geometries used. These geometries are dictated by the windows on a pressure vessel in which the samples are mounted.

References

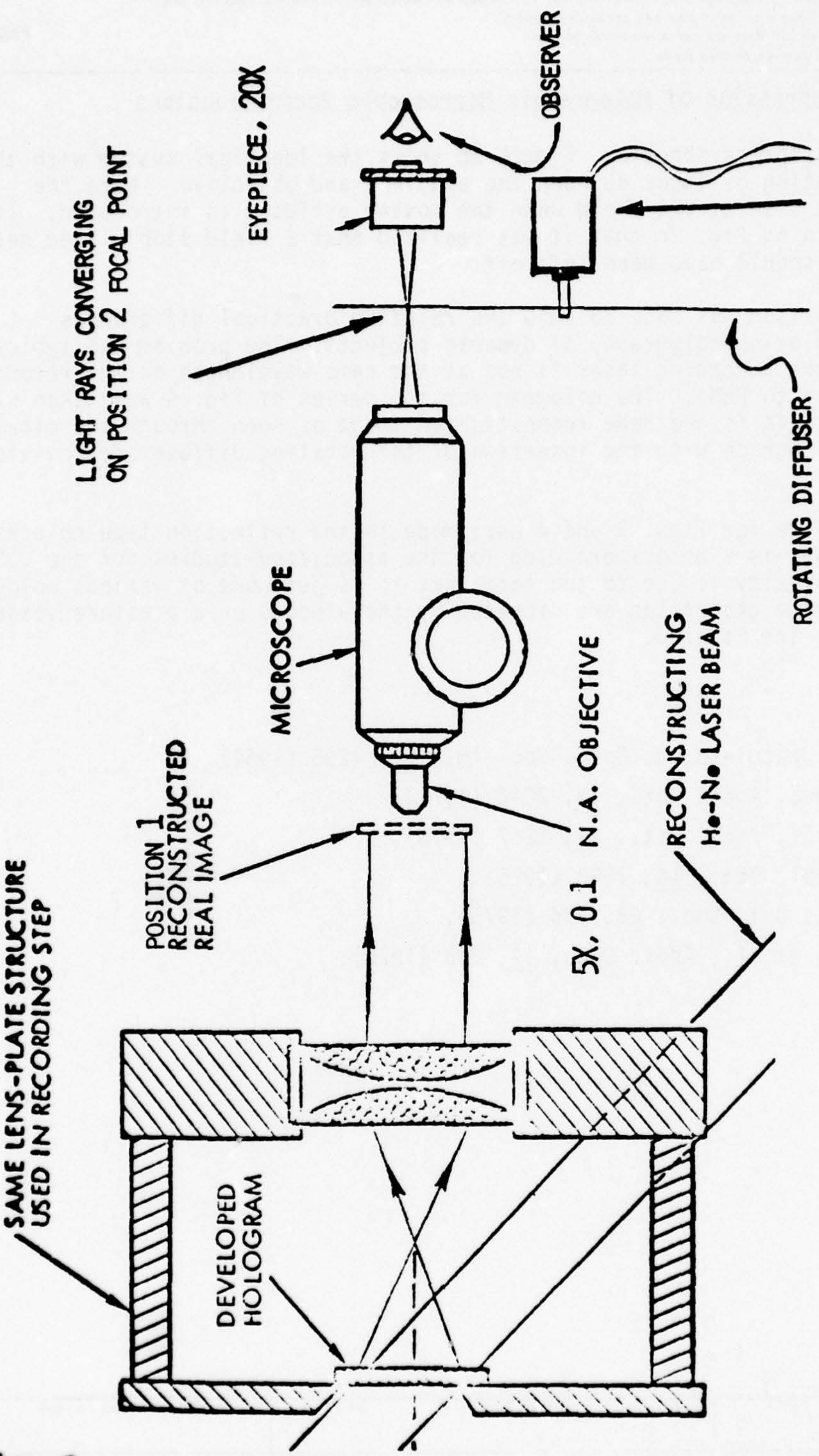
1. E. Leith and J. Upatnieks, J. Optc. Soc. Am., 54, 1295 (1964).
2. Tsuneda and Takeda, Appl. Opt., 13, 2046 (1974).
3. Ioka and Kurahashi, Appl. Opt., 14, 2267 (1975).
4. Kato, et al., Appl. Opt., 14, 1093 (1975).
5. Sato and Kato, J. Opt. Soc., 65, 856 (1975).
6. C. Roychoudhuri, et al., Appl. Opt., 14, 205 (1975).

INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE
R.A.Briones	3-2-77				

WITNESSED, READ AND UNDERSTOOD BY R.F.Wuerker 3/3/77 AND BY ______

R.F.Wuerker WITNESS DATE L.O.Heflinger WITNESS DATE

Title: Speckle Suppression of Holographic Microscopic Reconstructions



Inventor: R.A. Briones 3-2-77
R.A. Briones Date

Witnessed, Read, and Understood by: R.F. Wuerker 3-8-77 and C.O. Heflinger
R.F. Wuerker Date C.O. Heflinger Date

Title: Speckle Suppression of Holographic Microscopic Reconstructions

Docket No. _______

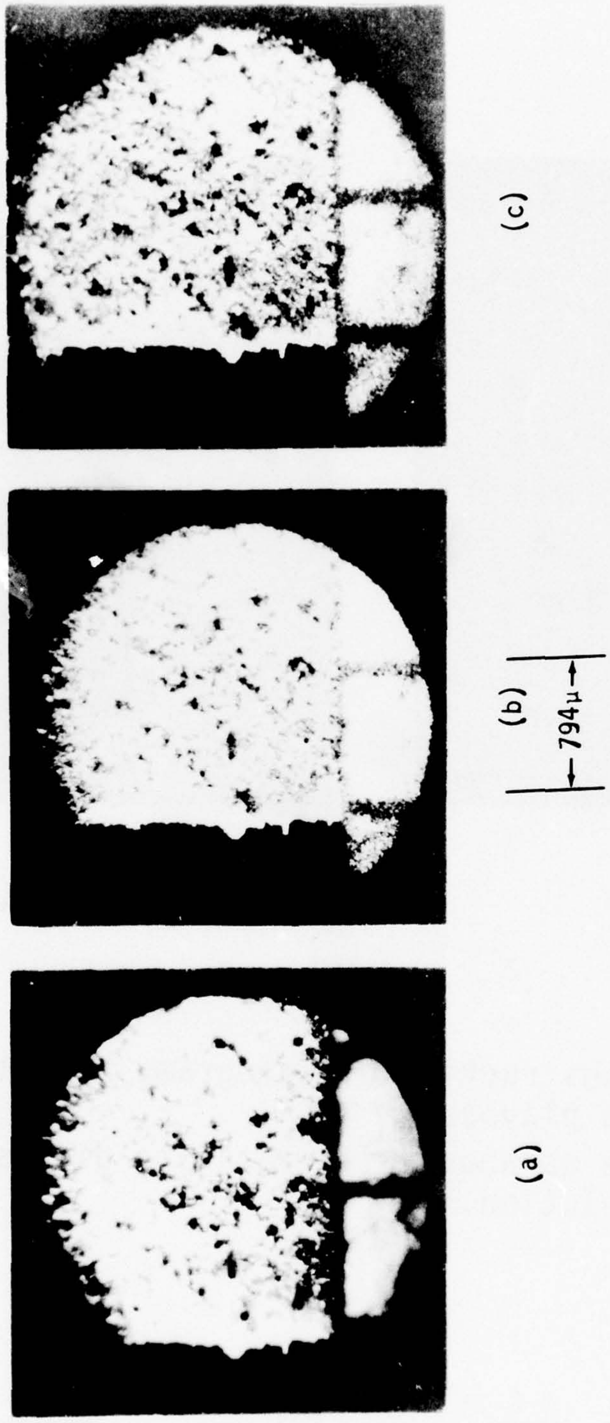
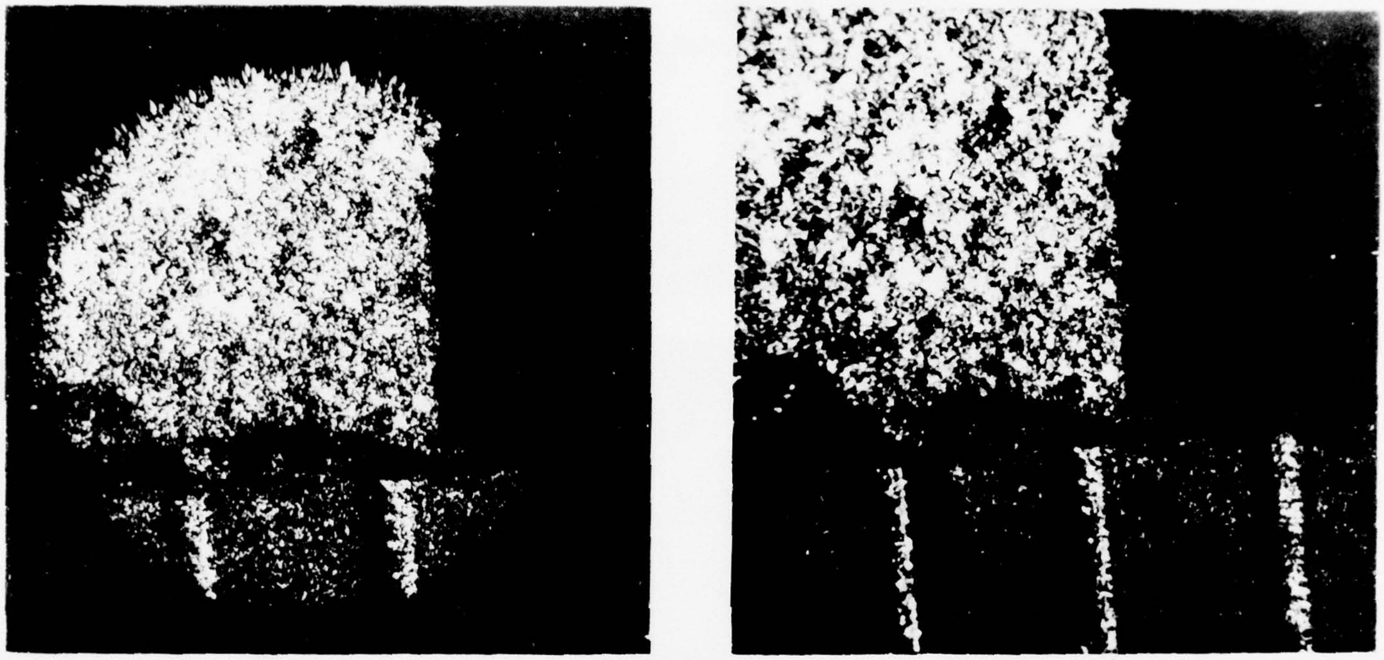


Figure 2. (a) White light illumination. Ruler in scene shows 1/32 inch/div.
(b) Coherent illumination, λ 6328 Å.
(c) Coherent illumination, λ = 6328 Å with moving diffuser.

INVENTORS: R.A. Briones 3-8-77 and ________
R.A. BRIONES DATE DATE

Witnessed, Read, and Understood by: L.O. Heflinger 3-8-77 and by R.F. Wuerker 3/3/77
L.O.Heflinger Date R.F.Wuerker Date



(a) (b)

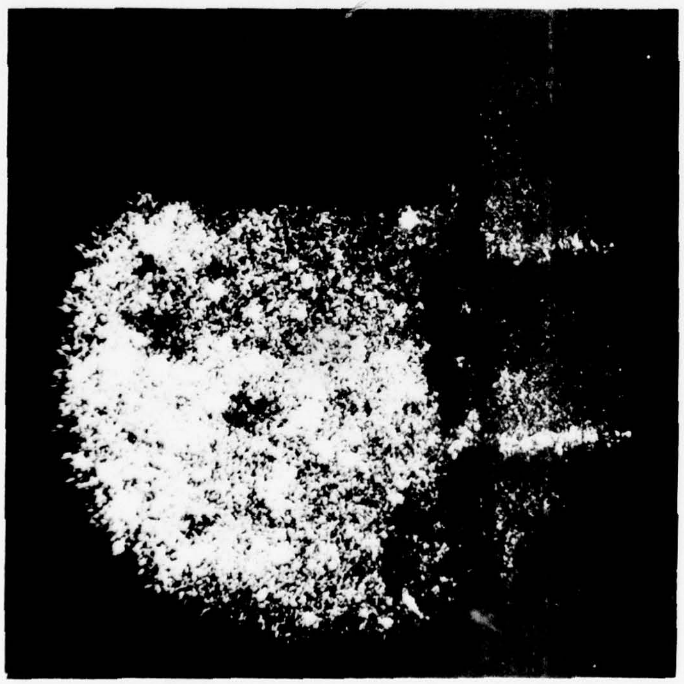
Figure 3. (a) Reconstruction of hologram, helium-neon recording, HeNe playback.
(b) Same as above with rotating diffuser to improve resolution.

INVENTORS: R.G. Briones 3-8-77 and ______
R.A. BRIONES DATE DATE

Witnessed, Read, and Understood by: L.O. Heflinger 3-8-77 and by R.F. Wuerker 3/3/77
L.O.Heflinger Date R.F.Wuerker Date

Title: Speckle Suppre ion of Holographic Microscopic Reconstructions

Docket No.____



(a)

(b)

Figure 4. (a) Reconstruction of hologram, recorded with ruby, playback HeNe.
(b) Same as adjacent picture, but including rotating diffuser to improve resolution.

INVENTORS: R.A. Briones 3-8-77 and ________ DATE

R.A. BRIONES DATE

Witnessed, Read, and Understood by: ________ 3-8-77 and by R.F. Wuerker 3/3/77

L.O.Heflinger Date R.F.Wuerker Date

Title: Speckle Suppression of Holographic Microscopic Reconstructions

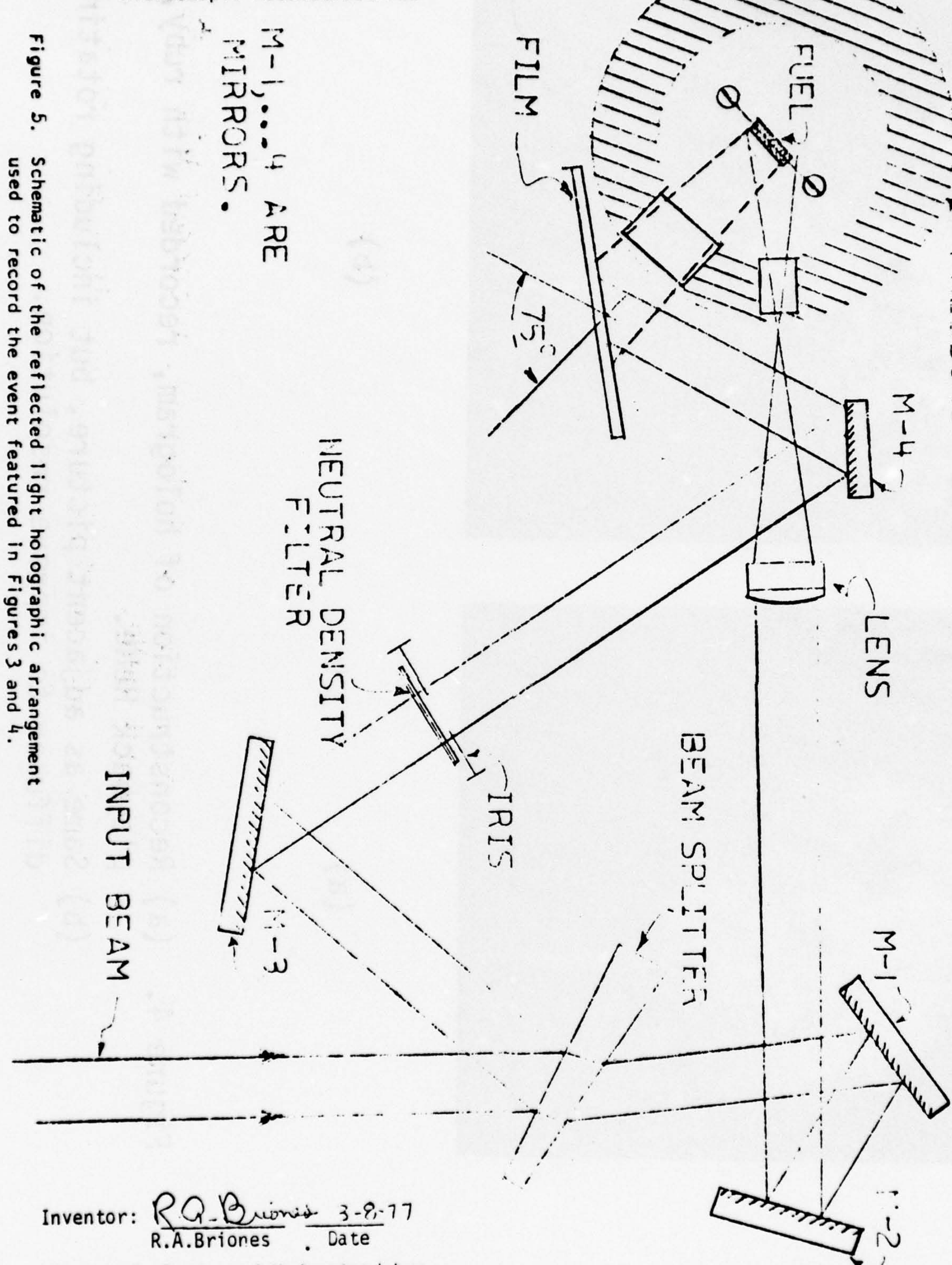


Figure 5. Schematic of the reflected light holographic arrangement used to record the event featured in Figures 3 and 4.

Inventor: R.A.Briones 3-8-77
R.A.Briones Date

Witnessed, Read, and Understood by:
R.F.Wuerker 3-8-77 and L.O.Heflinger 3-8-77
R.F.Wuerker Date L.O.Heflinger Date

APPENDIX IX

ACTIVE DOUBLE REFERENCE BEAM HOLOCAMERA

TRW

DOCKET NO. 11054

NEW TECHNOLOGY REPORT FORM
(INVENTIONS & INNOVATIONS)

COMPLETE BOTH SIDES OF FORM
SEE INSTRUCTIONS, PAGE 2
MAIL TO TRW SYSTEMS AND ENERGY PATENT COUNSEL (E2/8014)

DATE 9-7-77

TITLE OF INVENTION/INNOVATION: Active Double Reference Beam Holocamera for Recording Separately Reconstructable Images

INNOVATOR(S)

FULL NAME (NO INITIALS)	(CITIZENSHIP)	BADGE NO.	S.S.NUMBER	TRW MAIL STA.	EXTENSION
Robert Albert Briones	U.S.	10525	568-40-1645	R1/1070	61370,61105

RESIDENCE (STREET)	(CITY)	(COUNTY)	(STATE)	(ZIP)
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IMMEDIATE SUPERVISOR	SECTION, DEPT, LAB., DIV.	CCC	TRW MAIL STA.	EXTENSION
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FULL NAME (NO INITIALS)	(CITIZENSHIP)	BADGE NO.	S.S.NUMBER	TRW MAIL STA.	EXTENSION
Ralph Frederick Wuerker	U.S.	32549	571-34-8432	R1/2020	51433

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IMMEDIATE SUPERVISOR	SECTION, DEPT, LAB., DIV.	CCC	TRW MAIL STA.	EXTENSION
George L. Clark	ATD/SGRS	4351	R1/1078	61370

FULL NAME (NO INITIALS)	(CITIZENSHIP)	BADGE NO.	S.S.NUMBER	TRW MAIL STA.	EXTENSION

RESIDENCE (STREET)	(CITY)	(COUNTY)	(STATE)	(ZIP)

IMMEDIATE SUPERVISOR	SECTION, DEPT, LAB., DIV.	CCC	TRW MAIL STA.	EXTENSION

CONTRACT OR PROJECT (IRAD, B&P, PMP, ETC.) INFORMATION

TITLE	PROJECT NUMBER	COMPLETION DATE
Application of Holography to Combustion Characterization of Solid Rocket Propellants		MONTH Dec YEAR 1977

CUSTOMER	CONTRACT NUMBER	TRW S/N	JOB NUMBER
USAF/Rocket Propulsion Lab	F04611-76-C-0053	29889	3349-99

BACKGROUND INFORMATION

LIST JOB NUMBERS USED FOR WORK RELATED TO THE INVENTION/INNOVATION

ENGINEER'S NOTEBOOK & PAGE NUMBERS: None

WHEN WAS INVENTION/INNOVATION FIRST CONCEIVED OR REDUCED TO A PRACTICE?
May, 1977 conceived.

HAS INVENTION/INNOVATION BEEN SOLD OR USED IN TRW PRODUCTS? NO X YES ☐ (IF YES, WHEN? WHERE? TO WHOM?)

POTENTIAL INDUSTRIAL AND COMMERCIAL APPLICATIONS

INDICATE APPROXIMATE STATE OF DEVELOPMENT: CONCEPT X DESIGN ☐ PROTOTYPE ☐ MODIFICATION ☐ IN PRODUCTION ☐ OTHER ☐

PUBLICATIONS DISCLOSING INVENTION/INNOVATION

TRW REPORTS, MEMOS, AND PROPOSALS (INCLUDE DATE, NUMBER, AND TITLE)
None

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JOURNAL ARTICLES: (NAME OF PUBLICATION, DATE OF ISSUE, PAGE NUMBERS)
--

MEETING/SYMPOSIA PRESENTATIONS: (SOCIETY, DATE OF PAPER, LOCATION)

TRW

INSTRUCTIONS:
1. Describe problem invention/innovation is designed to solve; reference similar devices.
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3. Give the advantages of the invention/innovation over devices presently known.
4. List the features of the invention/innovation that are believed to be novel.
5. If more space is needed, use additional copies of this form.

DOCKET NO. ______

PAGE 1 OF 1

TITLE: DOUBLE REFERENCE BEAM HOLOCAMERA FOR RECORDING SEPARATELY RECONSTRUCTABLE IMAGES

Work on Contract F04611-76-C-0053 demonstrated that double exposure holography offers a unique way to determine the velocity of small particulate. Single reference beam-double exposure holograms have little certainty about the particle motion due to the fact that both images are reconstructed simultaneously. This is particularly the case when the particle field is dense and particles are not moving in the same direction Instead, one would like images that can be separately reconstructed. This need (or requirement) was realized by the construction of a holocamera with two reference beams. The optical arrangement is shown in Figure 1 (i.e., Figure 17 from JANNAF paper).

After the beam splitter, an optical switch (Pockel cell and beam-splitting polarizer) chose one of the two possible reference beam paths. The Pockel cell was electrically switched to its half-wave voltage between the two laser pulses. As a result, the second reference pulse was diverted along the second reference beam path. A quartz half-wave plate in this path repolarized the second laser pulse so that it was parallel and coherent with the scene laser pulse. With this arrangement, each pulse of the laser is recorded as a hologram of a spatially different reference beam. Both holographic images are recorded on top of each other on the same photosensitive plate. However, unlike single reference beam holograms, the two images can be separately reconstructed.

Reconstruction is as with a single reference beam hologram, except now two counter-propagating reference beams are directed through the double-exposed plate. One beam reconstructs one of the 3-D images. The beam from the second angle reconstructs the second image. Now the two images can be played back in sequence. Individual particle images can be seen to jump. Their displacements can be measured, and their velocities unquestionably computed from the known pulse separation.

The technique was actually tested and found to work. Holograms of MX-70 propellant burning at 34 atmospheres showed that the particulate was moving at velocities of $\sim$ 6 meters/second.[*]

The multiple reference beam technique shown in Figure 1 could easily be extended to include at least two more frames. For laser-pulses separated by 10 microseconds, such a holocamera would have a 100,000 frame per second rate.

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* R. A. Briones and R. F. Wuerker, "Holography of Solid Propellant Combustion," 14th JANNAF Combustion Meeting, Colorado Springs, Colorado, August 15-19, 1977.

INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE
R.A. Briones		R.F. Wuerker	[illegible]		

WITNESSED, READ AND UNDERSTOOD BY ______ G.L.Clark WITNESS ______ DATE

AND BY: ______ L.O.Heflinger WITNESS ______ DATE

SYSTEMS 125 REV. 12 76 (PAGE 2)

Double Reference Beam Holocamera for Recording
Separately Reconstructable Images

DOCKET NO. __________
Page 2 of 2

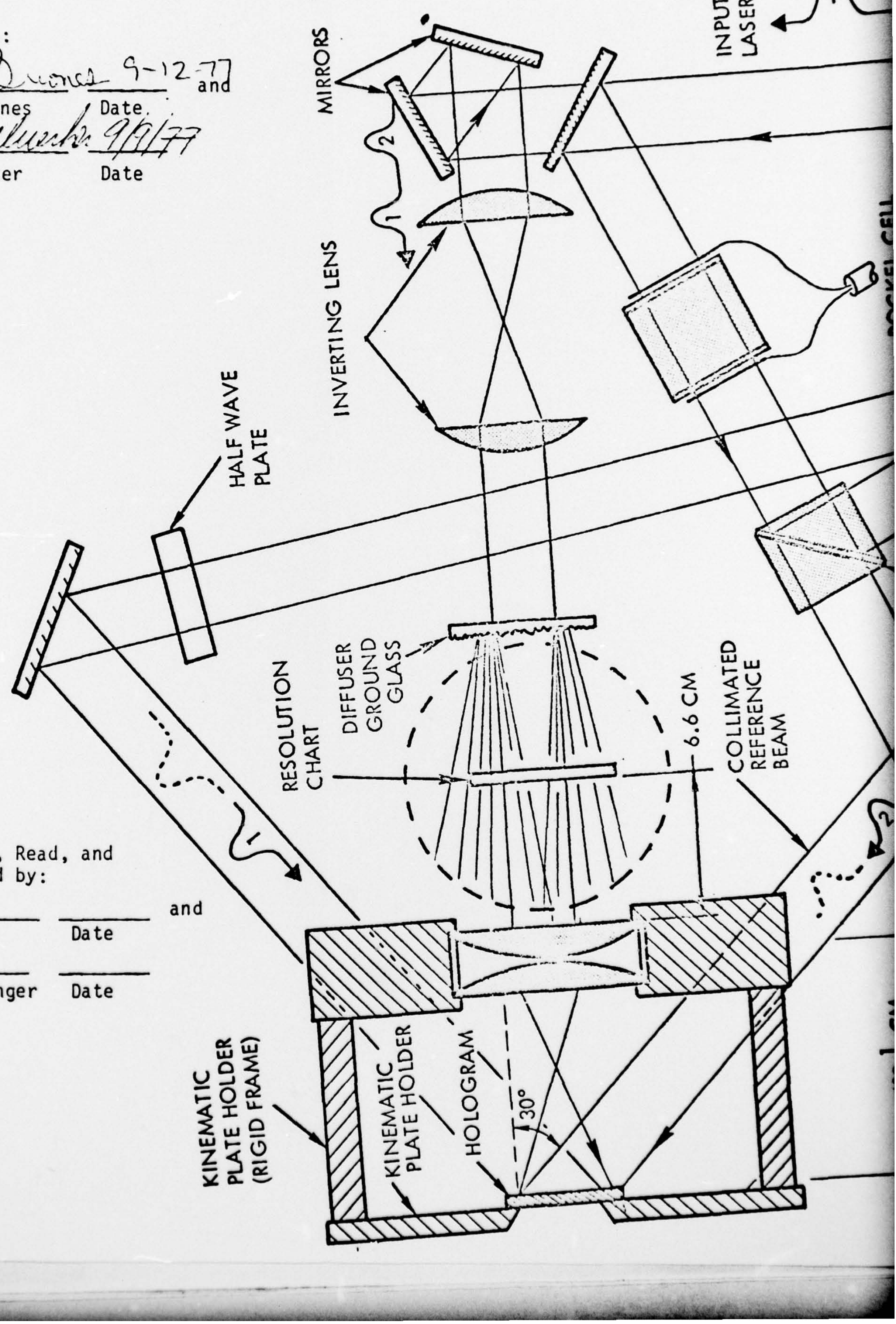
INVENTORS:

R.A. Briones 9-12-77 and

R.A. Briones Date

R.F. Wuerker 9/9/77

R.F.Wuerker Date



Witnessed, Read, and
Understood by:

__________ __________ and

G.L.Clark Date

__________ __________

L.O.Heflinger Date

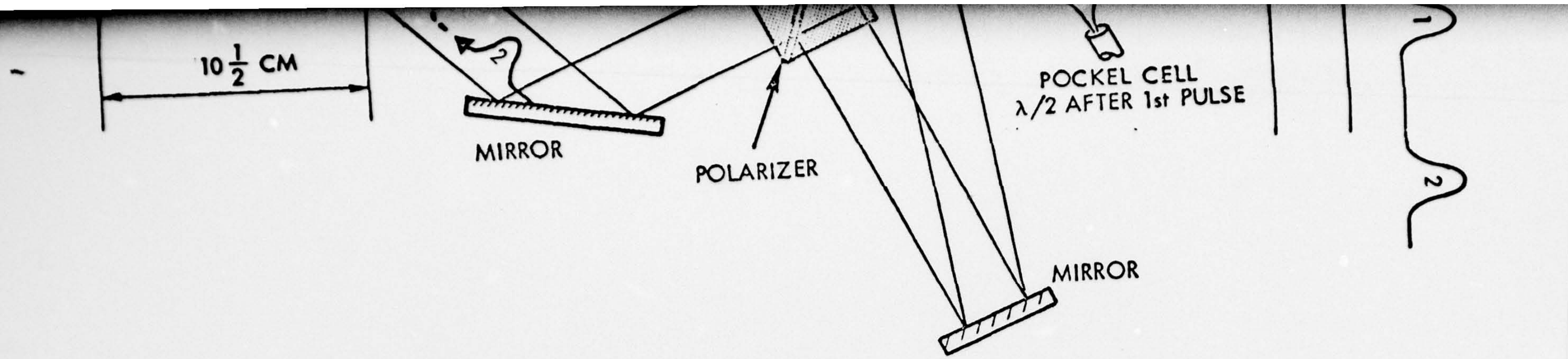


Figure 1. Schematic of new lens-assisted double reference beam holocamera for recording separately reconstructable rapid double exposure images on a single plate.

APPENDIX X

PASSIVE DOUBLE REFERENCE BEAM HOLOCAMERA

TRW
DEFENSE AND SPACE SYSTEMS GROUP

DOCKET NO. 11055

NEW TECHNOLOGY REPORT FORM
(INVENTIONS & INNOVATIONS)

COMPLETE BOTH SIDES OF FORM
SEE INSTRUCTIONS, PAGE 2
MAIL TO: TRW SYSTEMS AND ENERGY PATENT COUNSEL (E2/8014)

DATE September 9, 1977

TITLE OF INVENTION/INNOVATION: Passive Double Reference Beam Holocamera for Recording Separately Reconstructable Images

INNOVATOR(S)

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IMMEDIATE SUPERVISOR	SECTION, DEPT, LAB., DIV.	CCC	TRW MAIL STA.	EXTENSION

CONTRACT OR PROJECT (IRAD, B&P, PMP, ETC.) INFORMATION

TITLE	PROJECT NUMBER	COMPLETION DATE
Application of Holography to Combustion Characterization of Solid Rocket Propellants		MONTH Dec. YEAR 1977

CUSTOMER	CONTRACT NUMBER	TRW S/N	JOB NUMBER
USAF/Rocket Propulsion Lab	F04611-76-C-0053	29889	3349-99

BACKGROUND INFORMATION

LIST JOB NUMBERS USED FOR WORK RELATED TO THE INVENTION/INNOVATION:

ENGINEER'S NOTEBOOK & PAGE NUMBERS: None

WHEN WAS INVENTION/INNOVATION FIRST CONCEIVED OR REDUCED TO A PRACTICE? May, 1977

HAS INVENTION/INNOVATION BEEN SOLD OR USED IN TRW PRODUCTS? NO [X] YES [ ] (IF YES, WHEN? WHERE? TO WHOM?)

POTENTIAL INDUSTRIAL AND COMMERCIAL APPLICATIONS

INDICATE APPROXIMATE STATE OF DEVELOPMENT: CONCEPT [X] DESIGN [ ] PROTOTYPE [ ] MODIFICATION [ ] IN PRODUCTION [ ] OTHER [ ]

PUBLICATIONS DISCLOSING INVENTION/INNOVATION

TRW REPORTS, MEMOS, AND PROPOSALS (INCLUDE DATE, NUMBER, AND TITLE)
Holographic System for the Study of Propellants - Phase III Program Plan, June 14, 1977
(to AFRPL, Edwards, CA, from TRW)

JOURNAL ARTICLES: (NAME OF PUBLICATION, DATE OF ISSUE, PAGE NUMBERS)
--

MEETING/SYMPOSIA PRESENTATIONS: (SOCIETY, DATE OF PAPER, LOCATION)
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TRW

INSTRUCTIONS

1. Describe problem invention/innovation is designed to solve; reference similar devices.
2. Summarize what it does and how it does it. If appropriate, attach signed, witnessed and dated prints, memos, reports, etc.
3. Give the advantages of the invention/innovation over devices presently known.
4. List the features of the invention/innovation that are believed to be novel.
5. If more space is needed, use additional copies of this form.

DOCKET NO. ________________

TITLE: Passive Double Reference Beam Holocamera for Recording Separately Reconstructable Images

Work on Contract F04611-76-C-0053 demonstrates that the velocity of small particles can be determined from a double exposure hologram. The technique has many advantages when flow field is nonuniform, such as around the wakes of aerodynamic bodies, or in combustion environment of solid propellants. The technique does not work when a single reference beam hologram is double-exposed. The two images reconstruct simultaneously and one has difficulty in locating the initial and final position of a given particle, particularly if the particle field is dense, and the motions are random.

Instead, the images should be separately reconstructed. A holographic arrangement with two reference beams, and with a Pockel cell to switch or choose the two possible reference paths was described.*

This disclosure describes a holocamera in which the reference beam directions are chosen by the polarization of the illuminating laser beam.** The holocamera also has a reflected light beam channel. The following pages are taken from the program plan named below.

---

* R. A. Briones and R. F. Wuerker, "Active Double Reference Beam Holocamera for Recording Separately Reconstructable Images," Invention Document of September 7, 1977.

** R. A. Briones and R. F. Wuerker, "Holographic System for the Study of Propellants," Phase III Program Plan, June 14, 1977.

INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE	INVENTOR OR INNOVATOR	DATE
R.A.Briones	9-12-77	R.F.Wuerker	9/12/77		

WITNESSED, READ AND UNDERSTOOD BY: ________ DATE ________ AND BY: ________ DATE ________

G.L.Clark WITNESS — L.O.Heflinger WITNESS

SYSTEMS 125 REV. 12-76 (PAGE 2)

HOLOCAMERA

The new holocamera is schematically diagrammed in Figure 1. It differs from earlier holocameras by the incorporation of a pair of assisting lenses and by the addition of a second independent reference beam.

The assisting lenses make possible the achievement of high resolutions when holograms are reconstructed by the reverse reference beam technique.* These relay lenses provide the numerical aperture needed to achieve high resolution. They need only be simple plano-convex lenses; however, achromats have been shown to be best when there is a change in wavelength on reconstruction.

With the two independent reference beam paths, two separately reconstructed images can be recorded on top of one another (i.e., on the same plate). The beam splitters that provides the reference beam are arranged so that they reflect only vertically- or horizontally-polarized light, respectively. This is achieved by tipping the beam splitters to the Brewster angle. As a result, each reflects only the light (15%) whose electric vector is parallel to the plane of the reflecting surface; neither reflects any of the orthogonally-polarized light. For the Figure 1 arrangement, the reference beam directions are chosen by the polarization direction of the input laser pulses.

As a result, two independent separately reconstructable images are recorded on the same plate. Holograms recorded on a rapid double exposure basis will show, on reconstruction, the particle field at two different intervals of time. Particle motions can be followed if the pulses are separated by time short enough (~ 10 microseconds) so that the particles have moved not more than five or ten diameters. Particle velocities follow naturally from such unique recordings.

The new holocamera is completely passive. It can be used with any linearly polarized solid state laser such as ruby, doubled ruby, doubled YAG, etc., whose output pulse polarization can be rotated with an external electronic half wave plate such as a Kerr cell or a Pockel cell.

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* Ibid (see in particular Figure 2).

INVENTORS: R.A. Briones 9-12-77 Date and R.F. Wuerker 9/12/77 Date

Witnessed, Read, and Understood by: ________ Date ________ and ________ Date ________

The new holocamera requires only a laser system that emits two orthogonally-polarized output pulses. The first pulse is reflected by the first beam splitter. None of it is reflected by the second beam splitter. Most of the light (0.72%) passes through the splitter into the scene beam portion of the holocamera. The holocamera records a hologram of the scene with a reference beam of positive angle with respect to the scene driection. The second orthogonally-polarized pulse is not reflected by the first beam splitter. Only the second Brewster angle splitter reflects a 15% portion of light and directs it along the second reference beam path (corresponding to the negative angle reference beam). The second hologram is recorded superpositioned over the first on the same photosensitive plate. After development, the two images can be separately reconstructed by re-illumination from the two different reference beam directions.

The holocamera can be used as a conventional holocamera by simply not rotating the polarization of the second pulse. It will then record conventional rapid double exposure holograms and holographic interferograms.

The reference beam mirrors have been physically placed so that the two reference beams are both spatially and temporally matched. The scene beam is similarly matched. Temporal matching permits recording of holograms with lasers of low temporal coherence. Spatial matching accommodates lasers of low spatial coherence (such as a Q-switched ruby laser). The two mirrors and the inverting lenses in the scene arm of the new holocamera were needed to spatially match the scene beam to both reference beams.

The scene is placed between the inverting lenses and the assisting lenses. Events are transilluminated by collimated scene light. This mode of illumination gives highest resolution (particularly for ruby holograms reconstructed with a helium-neon laser of 10% shorter wavelength). Diffuse illumination will be achieved by inserting a piece of ground glass just after the last inverting lens (or anywhere behind the subject).

The assisting lenses provide the numerical aperture needed for microscopic resolutions. Narrow band filters (transparent to the laser

INVENTORS: R.A. Briones 9-12-77 Date and R.F.Wuerker 9/12/77 Date

Witnessed, Read, and Understood by: ________ G.L.Clark ________ Date and ________ L.O. Heflinger ________ Date

light, but reflecting at all other wavelengths) are placed between the two assisting lenses. These filters in concert with the mechanical shutter reduce the flame light to below the laser light levels.

The assisting lenses and the hologram plate holder are fixed rigidly together so that the combination is considered to be a single optical element. The two will be mounted so that they can be withdrawn as a unit for the purposes of loading fresh plates or for reconstructing already processed holograms.

The holocamera will also be provided with a reflected light option. This is also diagrammed in Figure 1. For reflected light recording, the second reference beam will be re-routed and used to record non-lens-assisted reflected light holograms. Since the first reference beam is undisturbed, it will be possible to make a simultaneous transmission hologram (provided the shutter synchronization problem is solved) and reflected light holograms of the same event. For such recordings, the holograms should be further covered with sheet polarizers to minimize fogging due to the non-used orthogonal polarized scene light.

The external appearance of the holocamera has been sketched in Figure 2.

In summary, the holocamera shown in Figures 1 and 2 and proposed for RPL for further solid propellant studies will have the following features:

- Superpositioned, but separately reconstructable, holograms.
  - For showing particle phenomena at two separate times.
- High resolution.
  - 2 microns for collimated illumination and for helium-neon laser reconstruction of ruby laser holograms.
  - 7 microns resolution for diffuse light holograms, ruby laser recorded and helium-neon reconstructed.
- Non-lens-assisted reflected light option
  - 10 micron resolution
  - Particles subject to holography's motion condition, "To be recorded, optical path must not change by more than one-tenth wave."

INVENTORS: R.A. Briones 4-12-77 Date and R.F. Wuerker 4/12/77 Date

Witnessed, Read, and Understood by: ________ G.L.Clark ________ Date and ________ L.O. Heflinger ________ Date

- Approximately five-inch diameter scene volume, to accommodate the bomb.

- Holograms are to be recorded on either 2 x 2-1/2 inch or 1 x 1-1/2 inch sensitized gel glass plates.

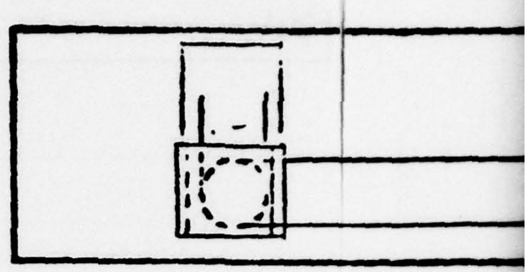
  - Single plate per loading.

- The assisting lenses and plate holder will be a single unit which can be easily removed from the holocamera for purposes of reloading with a new plate or for reconstructing the hologram.

  - A mechanical shutter will be a part of this assembly and will also serve to fire the laser.

INVENTORS: R.A. Briones 9-12-77 and R.F. Wuerker 9/12/77
R.A. Briones Date R.F.Wuerker Date

Witnessed, Read, and Understood by: ________ 147 ______ and ____________ ______
G.L.Clark Date L.O. Heflinger Date



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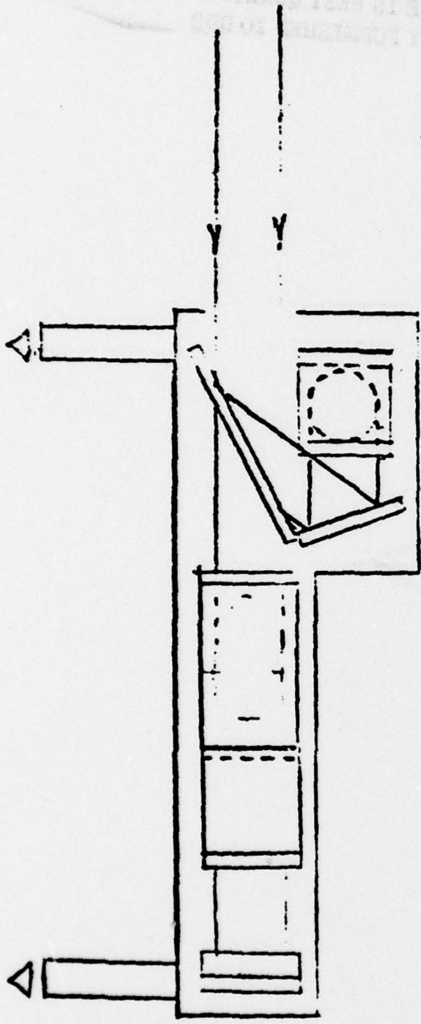

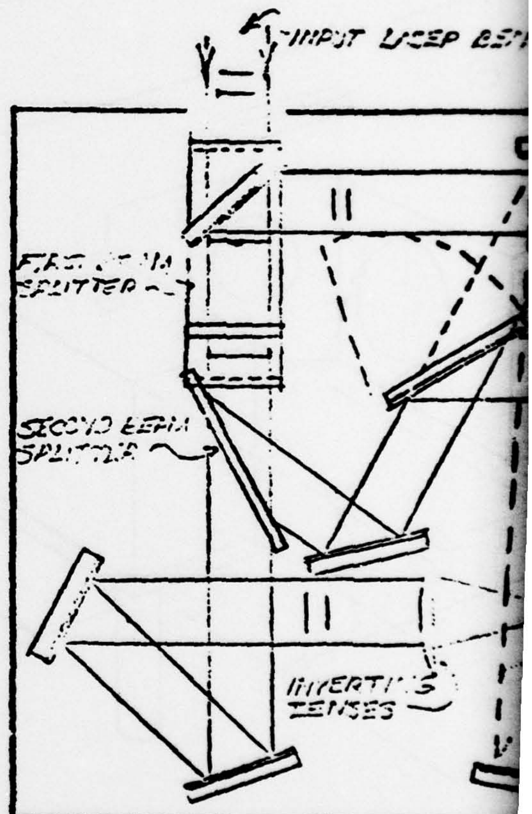

INVENTORS: R.A. Briones 9-12-77 and R.F. Wuerker 9/12/77
R.A.Briones Date R.F.Wuerker Date

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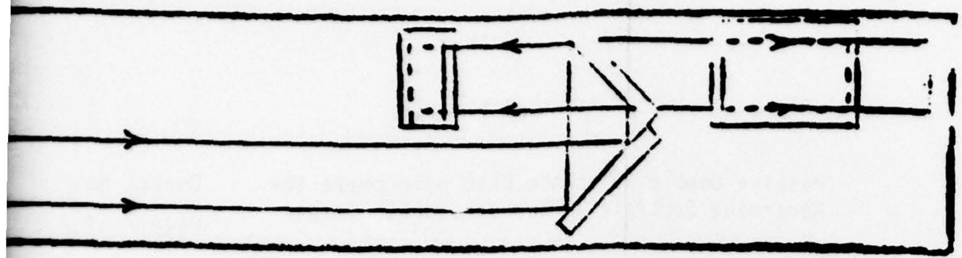
FIGURE I. DOUBLE IMAGE - LENS ASSISTED - HIGH RESOLUTION HOLOCAMERA



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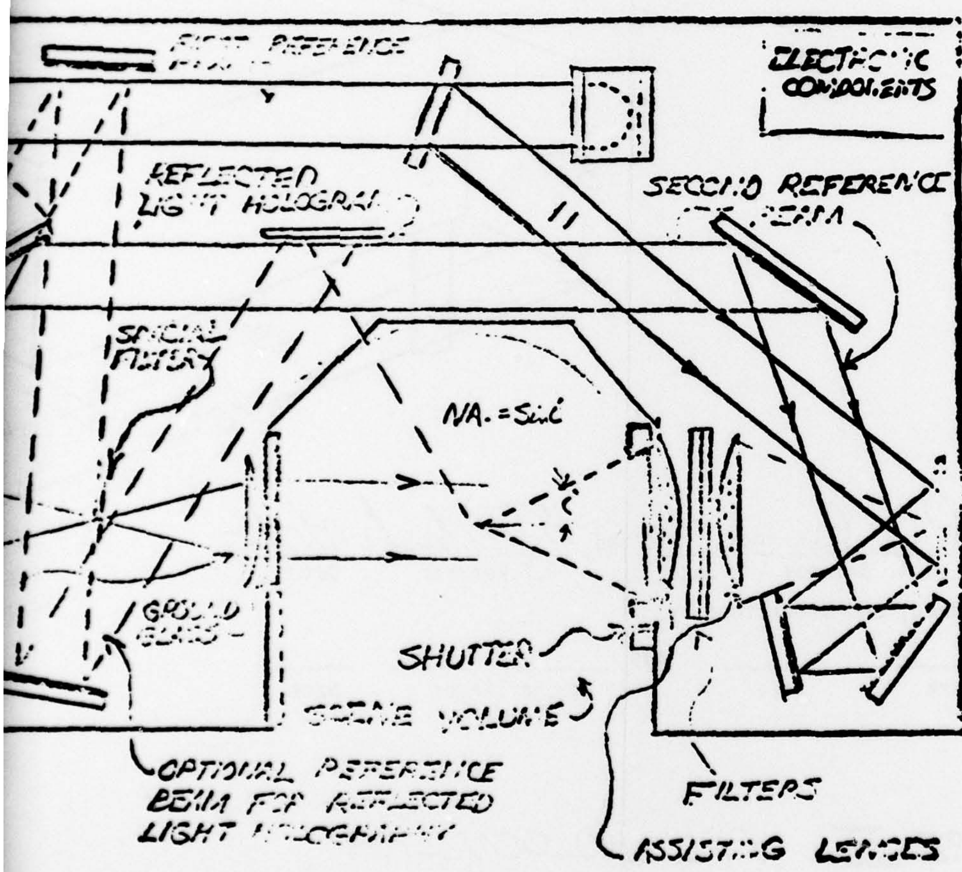

ORIGINATOR	DATE	TITLE	ENGINEERING SKETCH
		Double Image - Lens Assisted - High Resolution Holocamera	TRW ONE SPACE PARK • REDONDO BEACH • CALIFORNIA
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MJO			SHEET 148 OF

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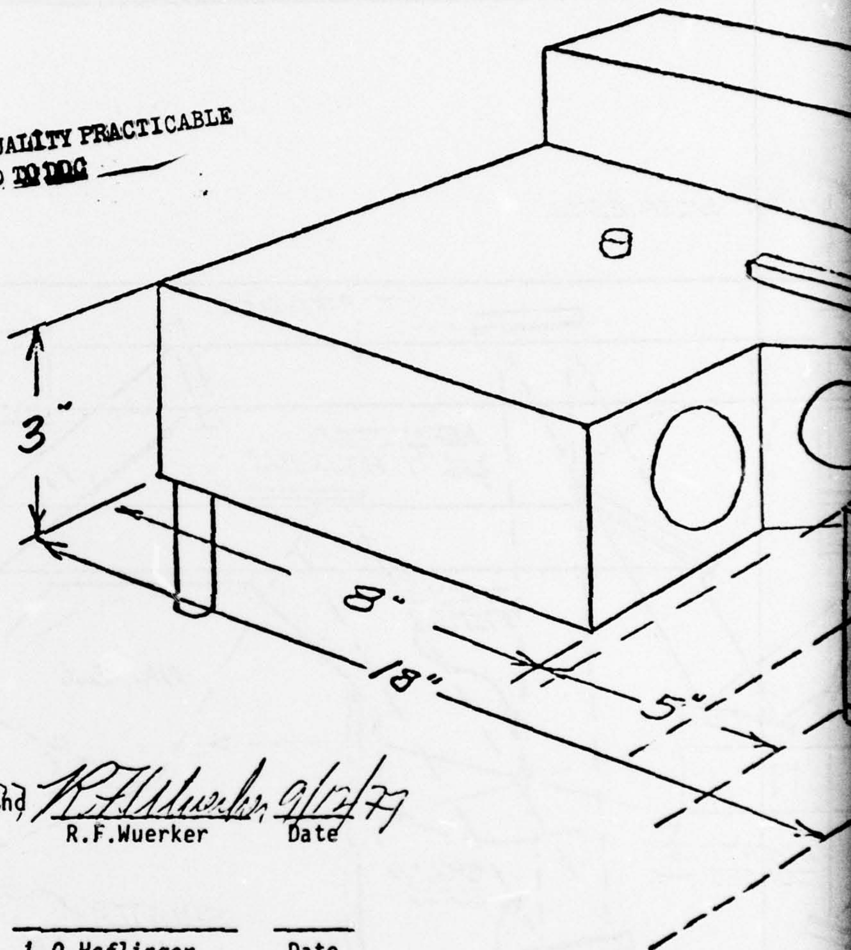

INVENTORS: R.A. Briones 9-12-77 and R.F. Wuerker 9/12/77

R.A. Briones Date R.F.Wuerker Date

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__________ ______ and __________ ______

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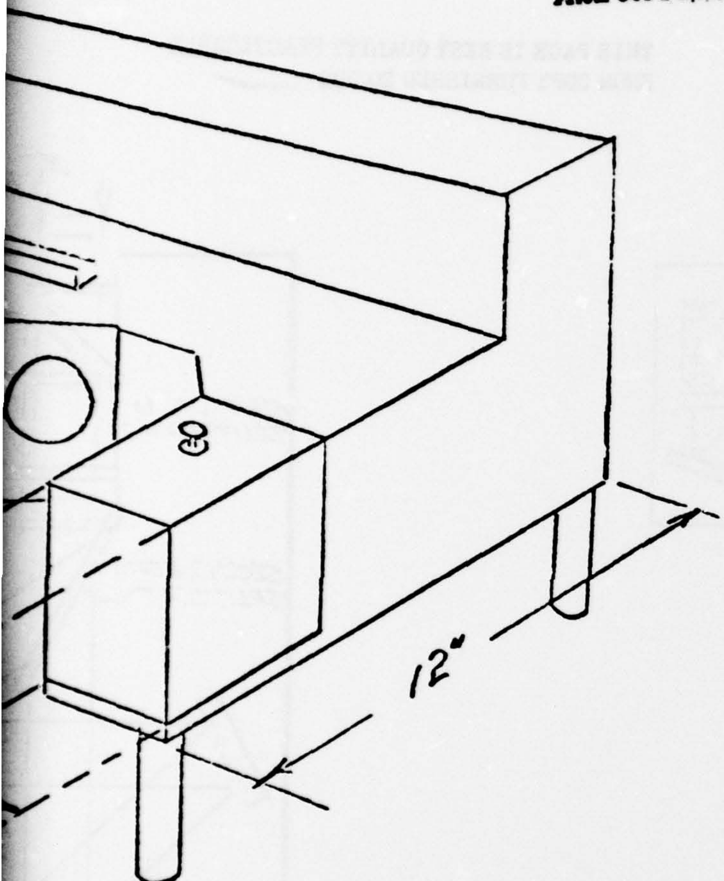
FIGURE II PPL HOLOCAMERA

LTR	DESCRIPTION	DATE	APPROVED



ENGINEERING SKETCH		TRW ONE SPACE PARK • REDONDO BEACH, CALIFORNIA 90278
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